Quasi-Periodic Fluctuations in X-ray and Gamma-ray during Solar Flares

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Abstract:

Solar flares are captivating yet complex phenomena, releasing vast amounts of energy and radiation into space. These energetic events have been studied extensively since the first recorded observation in 1859. Advances in observational techniques, from balloons and rockets to modern space-based telescopes, have provided unprecedented insights into the processes driving solar flares, including the acceleration of energetic particles and the heating of plasma to millions of degrees. Understanding the fast-time variations in X-ray and gamma-ray emissions during these flares is crucial for unraveling the underlying mechanisms of particle acceleration and energy release. The study of fast-time variations in X-ray and gamma-ray emissions during solar flares, particularly the phenomenon of quasi-periodic pulsations, has provided valuable insights into the complex processes of particle acceleration, energy release, and plasma dynamics in the solar atmosphere. Continued observations and advancements in instrumentation will further our understanding of these captivating solar phenomena.

QPPs in Solar Flares

Impulsive Phase

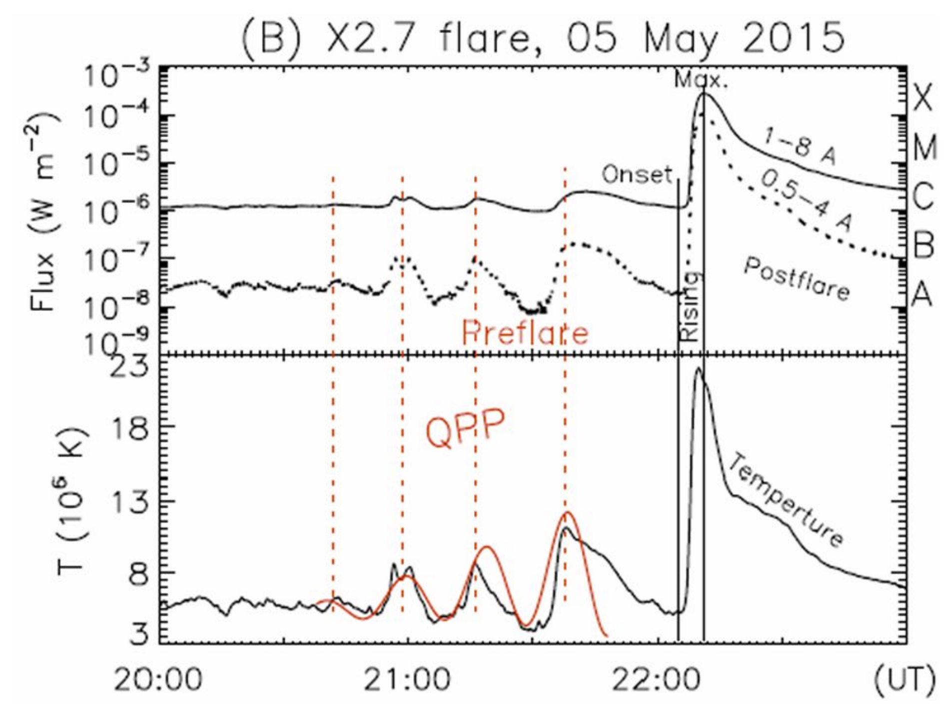
QPPs observed during the impulsive phase of solar flares often exhibit significant variations in emission intensity, sometimes exceeding 80% modulation depth. These rapid fluctuations provide valuable insights into the particle acceleration processes occurring in the flaring region.

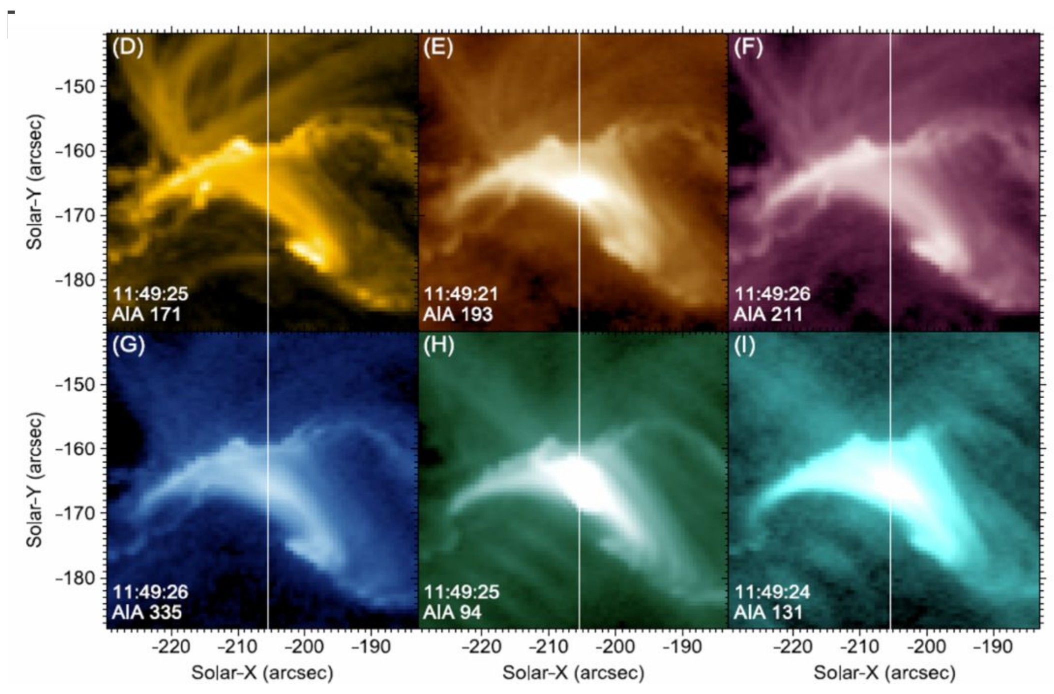
Decay Phase

QPPs observed during the decay phase of flares typically display characteristics of decaying quasi-harmonic signals, where the signal decay time is proportional to the oscillation period. This relationship between signal decay and oscillation period has […] observed in both solar and stellar flares.

Widespread Occurrence

QPPs have been detected in a wide range of wavelengths, from radio to gamma-rays, suggesting that they impact every layer of the solar atmosphere, from the chromosphere to the corona. Statistical studies have found that a significant percentage of large solar flares exhibit QPP signatures.





Observations of Fast-Time Variations

Subsecond Spikes

Observations have revealed the presence of rapid, subsecond spikes in hard X-ray emissions during solar flares, with some spikes as narrow as 45 milliseconds. These findings impose significant constraints on the timescales associated with non- thermal particle acceleration models.

Spectral Evolution

High-energy gamma-ray observations have revealed rapid spectral evolution of accelerated ions on timescales of approximately 30 seconds, mirroring the spectral changes observed in the lower- energy bremsstrahlung continuum.

Fast time variations

QPPs with periodicities ranging from a few seconds to several minutes have been frequently observed in solar flare emissions, spanning a wide range of wavelengths, including radio, optical, soft X-ray, and hard X - ray / gamma -ray bands

Late-Phase Emission

An extended late-phase gamma- ray emission phenomenon has been identified, occurring subsequent to the impulsive phase and lasting for tens of minutes to tens of hours. This late-phase emission is associated with the occurrence of fast coronal mass ejections.

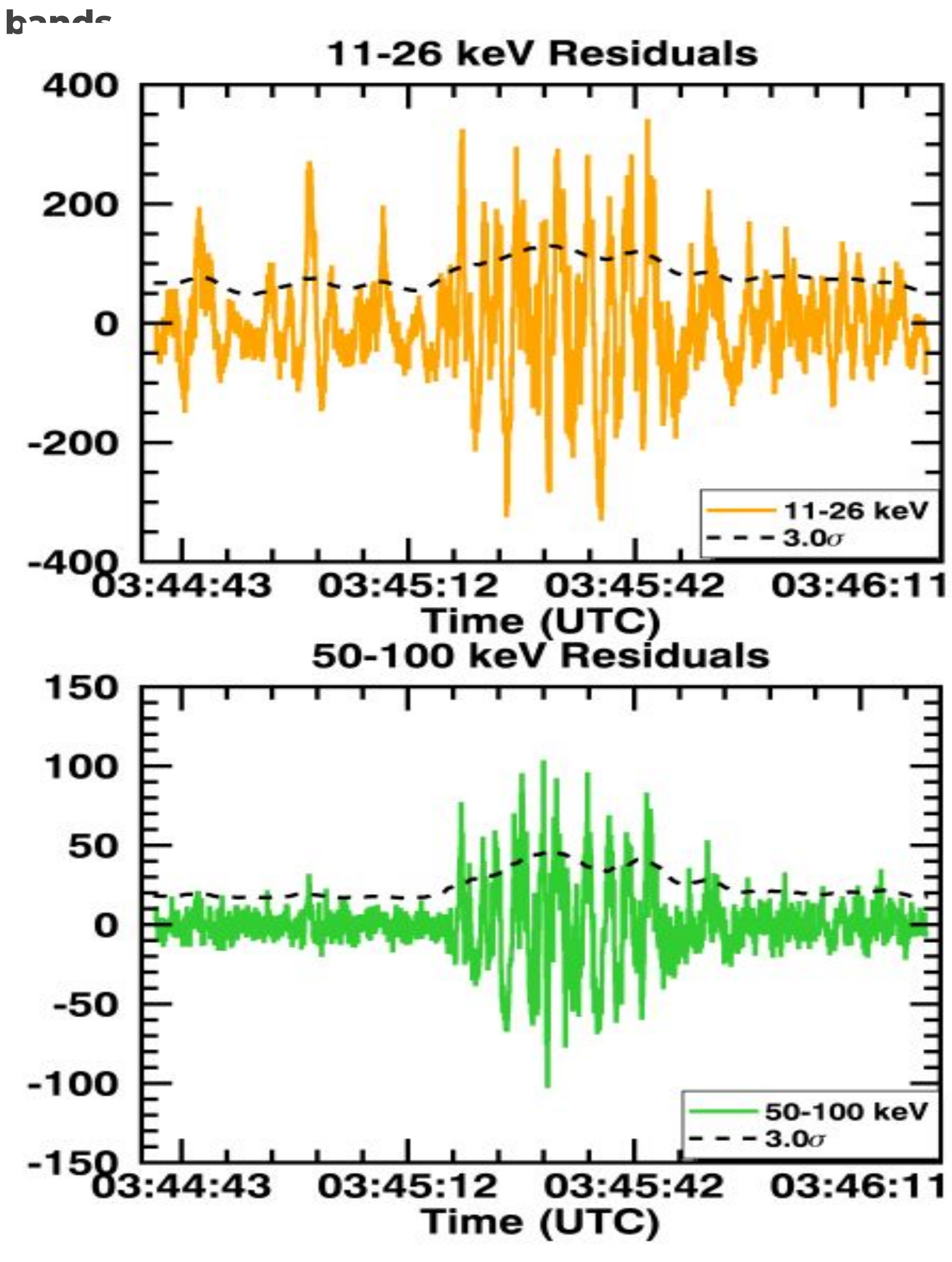


Fig: Subsecond fluctuations from Knuth, T., & Glesener, L. (2020)

Theoretical Models for QPPs

Oscillatory Processes

QPPs can be explained by various oscillatory processes, such as magnetohydrodynamic (MHD) oscillations, dispersive wave trains, and oscillations analogous to electrical LCR circuits. These processes are driven by the interplay between inertia and restoring forces within the flaring plasma.

Self-Oscillatory Processes

Alternatively, QPPs can arise from self- oscillatory processes, such as periodic or repetitive spontaneous reconnection, thermal overstabilities , and wave- driven reconnection. These processes are driven by the internal dynamics of the flaring system, rather than external perturbations.

Autowave Processes

Autowave processes , characterized by self - sustained propagation through the medium, can also contribute to the observed quasi-periodic behavior in solar flares. Slow magnetoacoustic waves and their interaction with magnetic reconnection have been proposed as a potential mechanism for the quasi- periodic progression of energy releases.

Statistical Studies of QPPs

Prevalence of QPPs

Statistical studies have found that a significant percentage of large solar flares, ranging from 30% to 90%, exhibit quasi-periodic pulsations (QPPs) in their emissions, particularly in the soft X-ray and EUV wavelength ranges.

Characteristic Periods

The typical periods of QPPs observed in solar flares range from a few seconds to several minutes, with the majority falling within the 10 to 30-second range, regardless of the flare magnitude.

Relationship to Flare Properties

While QPP periods do not seem to correlate with the overall flare magnitude, they have been found to be related to various properties of the flare ribbons, such as area, separation, and magnetic flux, providing insights into the underlying mechanisms.

Instruments Observing Fast-Time Variations

RHESSI

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) has provided high - resolution hard X - ray imaging spectroscopy and gamma-ray line spectroscopy, enabling detailed studies of particle acceleration and energy release during solar flares.

Hinode XRT

The Hinode X-Ray Telescope (XRT) is a high-resolution instrument designed to study the Sun's corona, contributing to our understanding of the thermal and dynamic processes occurring during flares.

Fermi GBM

The Gamma-ray Burst Monitor (GBM) on the Fermi Gamma-ray Space Telescope has provided valuable data on the fast-time variations in X-ray and gamma-ray emissions during solar flares, despite some limitations in its optimization for solar observations.

Solar Orbiter STIX

The Spectrometer/Telescope for Imaging X-rays (STIX) on the Solar Orbiter mission offers high-time-resolution observations of the hard X-ray emission from solar flares, enabling the study of rapid fluctuations and particle acceleration processes.

References:

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