Giant spike count variability in two-dimensional Neuron models

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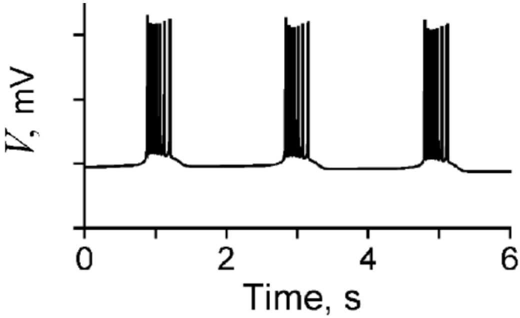
Neurons and Bursting

- 100 billion neurons in human brain
- neurons transmit information via spiking activity
- spike = abrupt change of membrane voltage (action potential) that propagates through axon



intrinsic bursting in a pacemaker neuron model (Rybak, 2004)

Goals of this project

- Overall goal: simulate bursting in simple neuron models and investigate spike count statistics
- in comparable systems (Brownian Particles, Lindner/Sokolov, 2016) critical points where firing pattern changes drastically
  $\rightarrow$can we find these here as well?
- simulate neurons under influence of periodic stimulus to explore signal transmission

Persistent sodium plus potassium $I_{Na,p} + I_K$ model

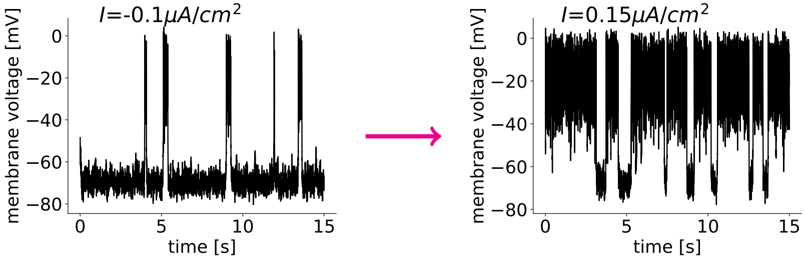
- simplest model for (stochastic) bursting: 2-d neuron model+noise
- electric activity in neurons relies on ionic currents through membranes
- $I_{Na,p} + I_K$ model:

$$C\dot{V} = I_{bias} - I_L - I_{Na} - n \cdot I_K + \sqrt{2D}\xi(t)$$
$$\dot{n} = (n_\infty(V) - n)/\tau$$

V...membrane voltage
n...gating variable of potassium channels
C...capacitance
I_L...leak current
n_∞...sigmoid-shaped activation function
D...noise intensity

Membrane voltage

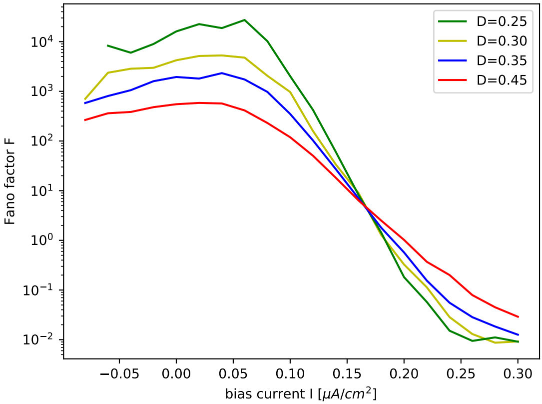
- system is bistable: resting and spiking states coexist
- noise induces transitions between states
- higher bias current favors spiking state
  $\rightarrow$ neuron bursts longer and more frequently:



Quantities of interest

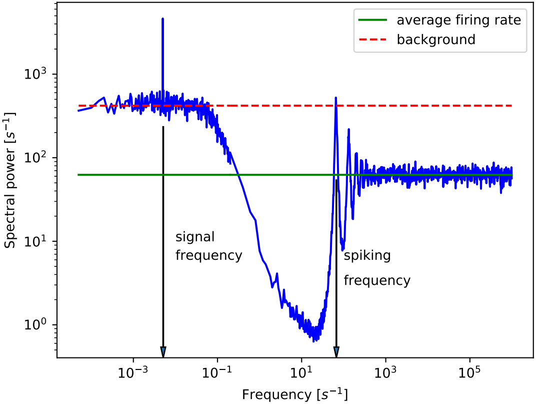
- System without signal
  - spike count $N(t)$: number of spikes after time t
  - spiking variability quantified by Fano factor: $F(t) = \frac{\langle \Delta N^2(t) \rangle}{\langle N(t) \rangle}$
- System with periodic signal
  - power spectrum $S(f)$ measures frequency of components in membrane voltage
  - signal-to-noise ratio (SNR) compares power of signal to background noise
  - weak+slow signal= $SNR \propto 1/F$
    $\rightarrow$ changes in Fano factor F have opposite effect on SNR

Count statistics



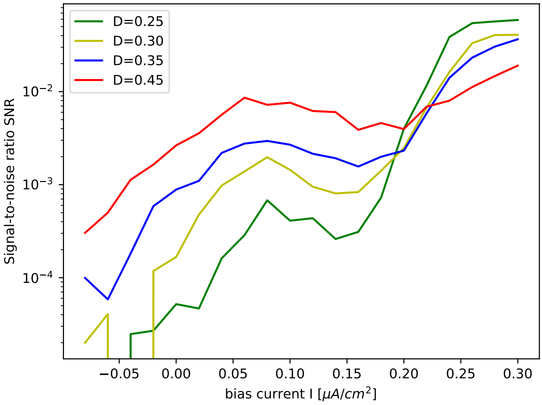
Fano factor at different noise intensities D. The intersection point forms the border between giant (left) and small (right) Fano factor F in the $D \to 0$ limit.

Power spectrum for system with signal



Power spectrum of the membrane voltage. A sharp spike can be seen at the signal frequency ($5 \cdot 10^{-3}$Hz) and a second maximum at the spiking frequency(10^2Hz)

Signal-to-noise ratio SNR



SNR at different noise intensities. As expected, a sharp increase is observed where Fano factor F becomes minimal.

Conclusion

- two-dimensional bistable neuron model turned into burster by adding noise
- critical current observed where Fano factor F drops strongly
- SNR grows by multiple orders of magnitude near critical current
  $\rightarrow$ bistable neurons in the critical regime can greatly enhance signal transmission via slight adjustment of currents