Quantifying the Effects of Weak Stellar Flybys on the Solar System

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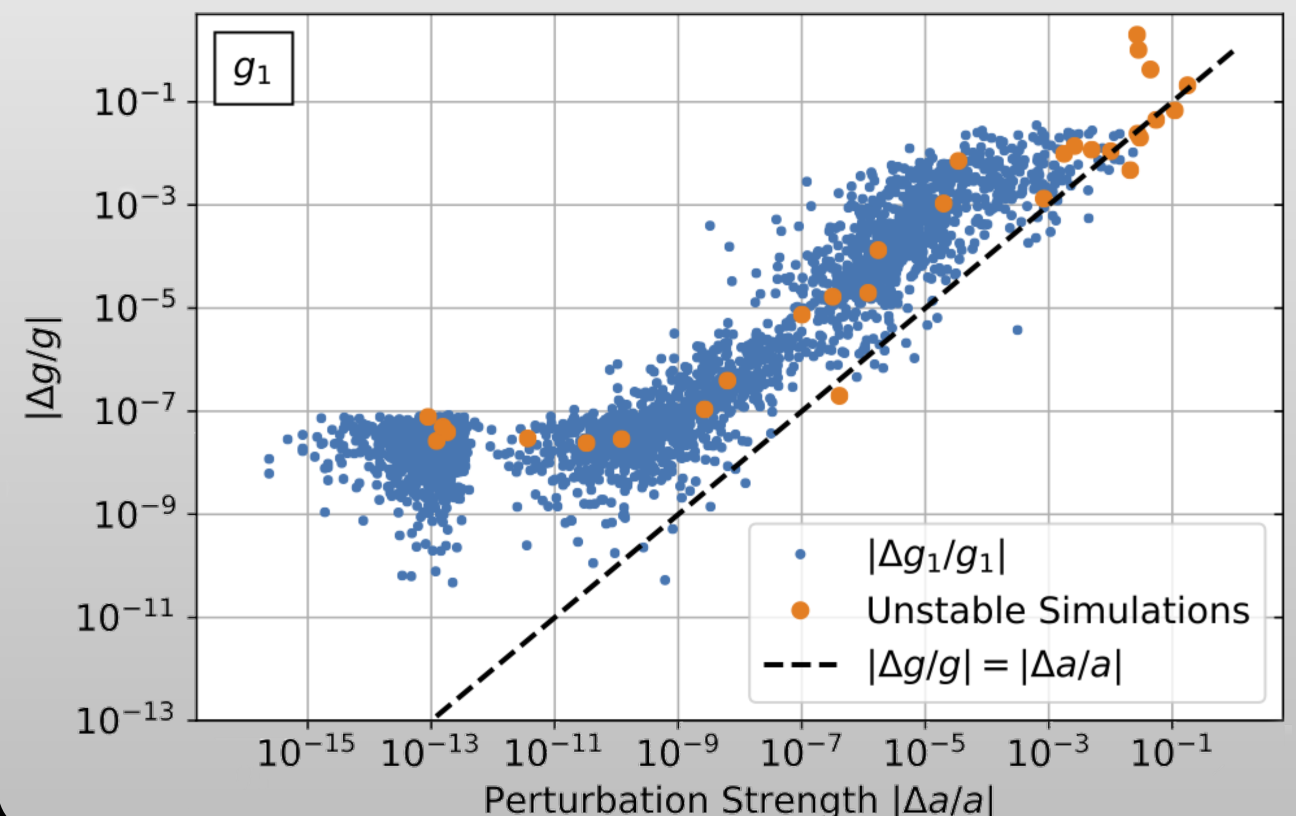
Summary

The architecture and evolution of planetary systems are shaped in part by stellar flybys. Within the context of the local stellar environment, we look at stellar encounters which are too weak to immediately destabilize the Solar System but are nevertheless strong enough to measurably perturb its dynamical state. We estimate the strength of such perturbations on a secularly evolving system using a simple analytic model and confirm those estimates with direct N-body simulations. We then run long-term integrations and show that even small perturbations from stellar flybys can significantly affect the stability of planetary systems over their lifetime. Specifically, our results show that relative perturbations to Neptune's semi-major axis on the order of $\gtrsim 10^{-3}$ are strong enough to increase the probability of destabilizing the inner Solar System within 5 Gyrs.

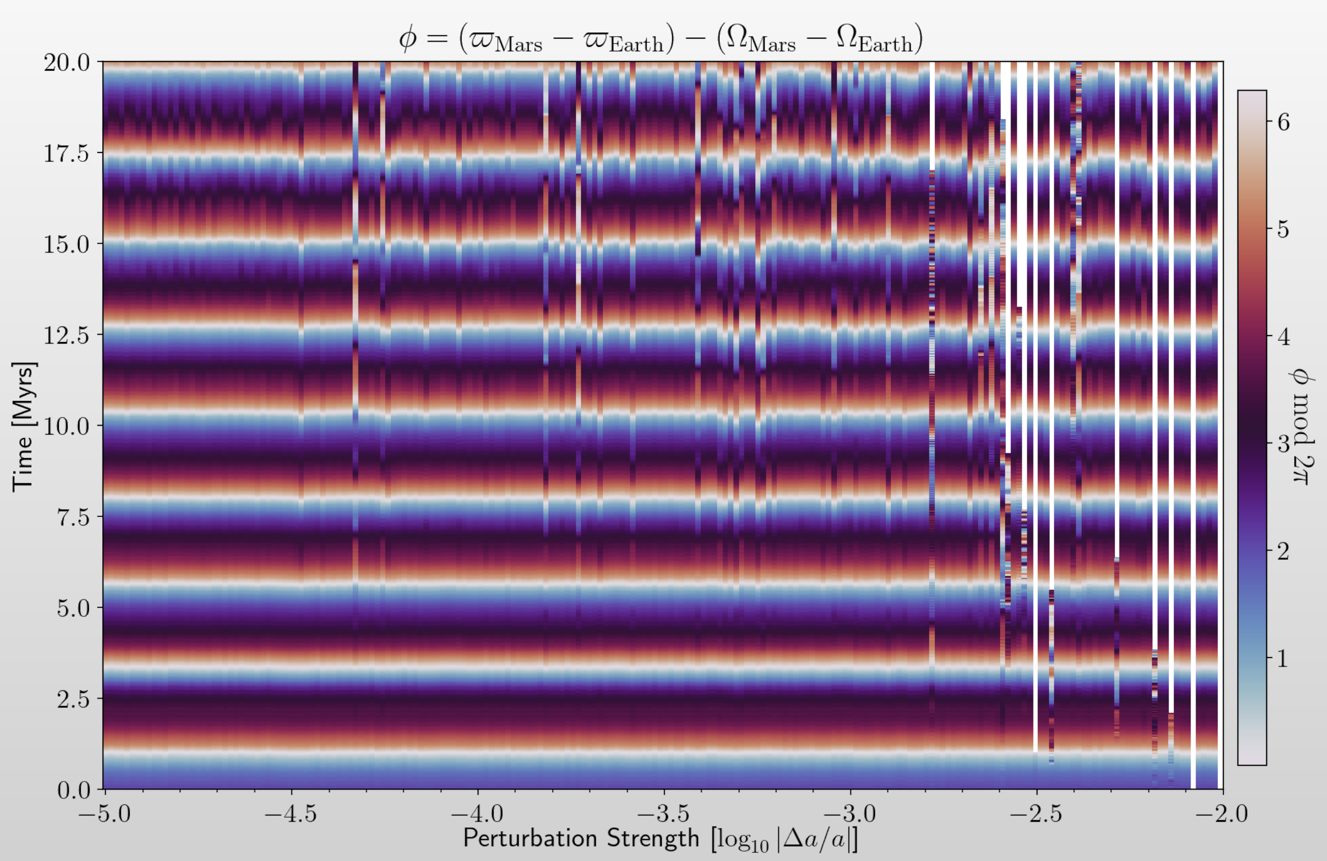
Motivation

Perturbations from a stellar flyby will be exponentially smaller for an inner planet than for an outer planet. Therefore, the changes in the secular frequencies will be dominated by the changes to the semi-major axis of the outer planet. The dynamics of the Solar System are primarily secular, so small changes can lead to secular resonances and instability.

$$\left|\Delta a/a\right| \propto f_1(e_\star)\left(a/q_\star\right)^{3/4} \exp\left[-\left(q_\star/a\right)^{3/2} f_2(e_\star)\right] \propto \left|\Delta g/g\right|$$



A Simple Example

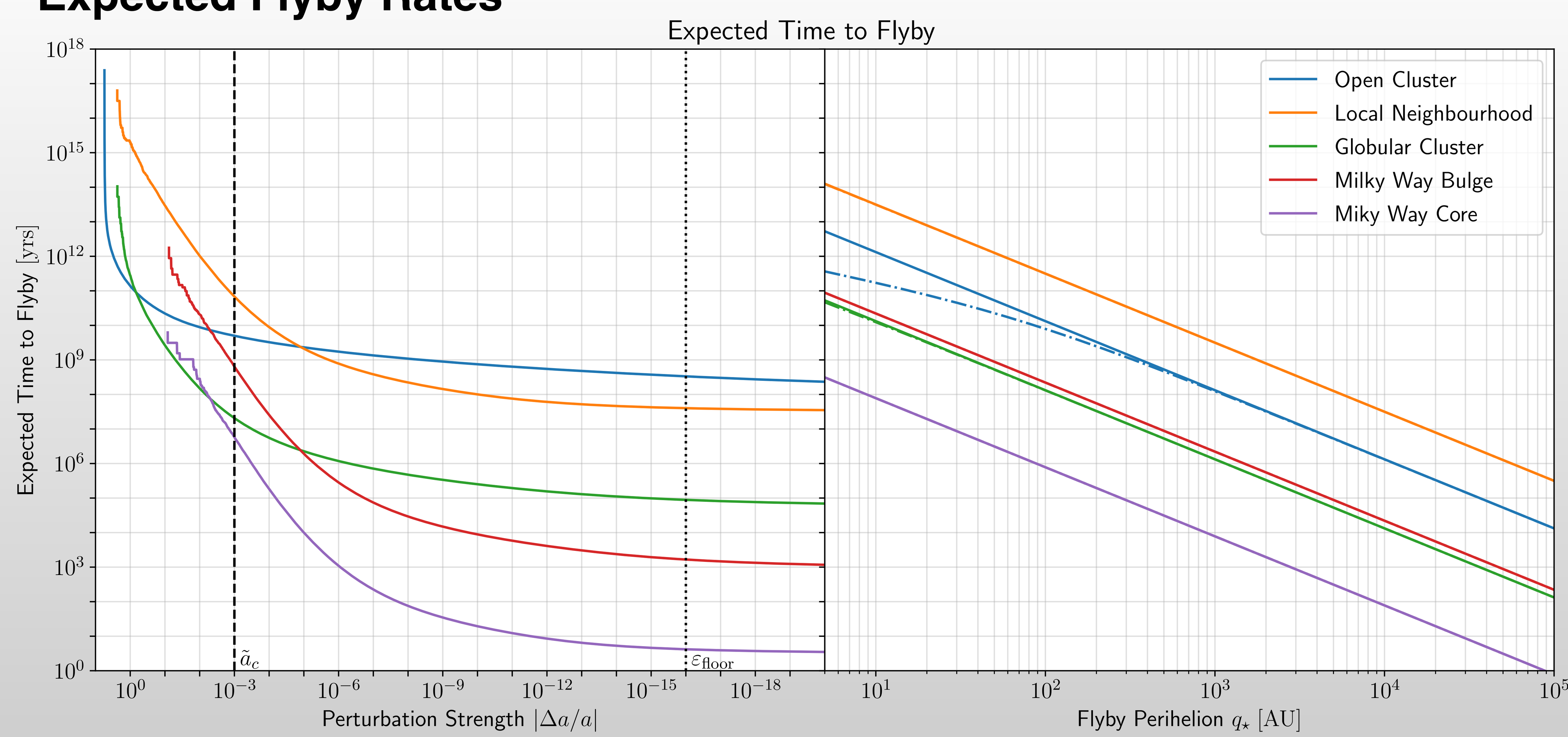


Earth-Mars secular resonances as a result of a perturbation to only Neptune's semi-major axis. This shows the time series data of the difference between phase angles for the linear combination of $\phi \bmod 2\pi$. The blank spaces towards the right side of the figure are from simulations that did not complete the 20 Myr integration due to a collision or escape.

Secular Resonances

Through the secular coupling of the Solar System, when the semi-major axis of one planet changes, all of the secular modes of the Solar System change by roughly the same order of magnitude. Mercury is only marginally stable and the chaotic diffusion of Mercury's orbit can result in instability within the lifetime of the Solar System. When the eccentricities and inclinations of all the planets are increased by 20%, the timescale for Mercury's instability shortens to 100 Myrs. As stellar flybys change the orbits of the planets, these perturbations can be transferred between the planets. In situations with weak but detectable perturbations to Neptune, Mercury is more likely to experience a secular resonance with Jupiter and cause the inner Solar System to become unstable. The $g_1 - g_5$ secular resonance between Mercury and Jupiter is the dominant mechanism for instability in our simulations. When these two secular modes fall into secular resonance, the eccentricity of Mercury increases on short timescales and can lead to Mercury-Venus collisions.

Expected Flyby Rates



The left panel shows the distribution of different perturbation strengths that are expected from various stellar environments. The thick dashed vertical line shows the critical relative perturbation strength, above which we expect a dramatic increase in Solar System instability. The thin dotted vertical line shows the minimum value that is resolvable by standard modern computers. The right panel shows the traditional view of the expected time to flyby based on the perihelion distance of the perturbing star. The dashed dotted lines show the effect of gravitational focusing. A comparison between the two panels demonstrates that perturbations of order unity are extremely rare and that the effects of stellar flybys on planetary orbits depend on much more than the perihelion.

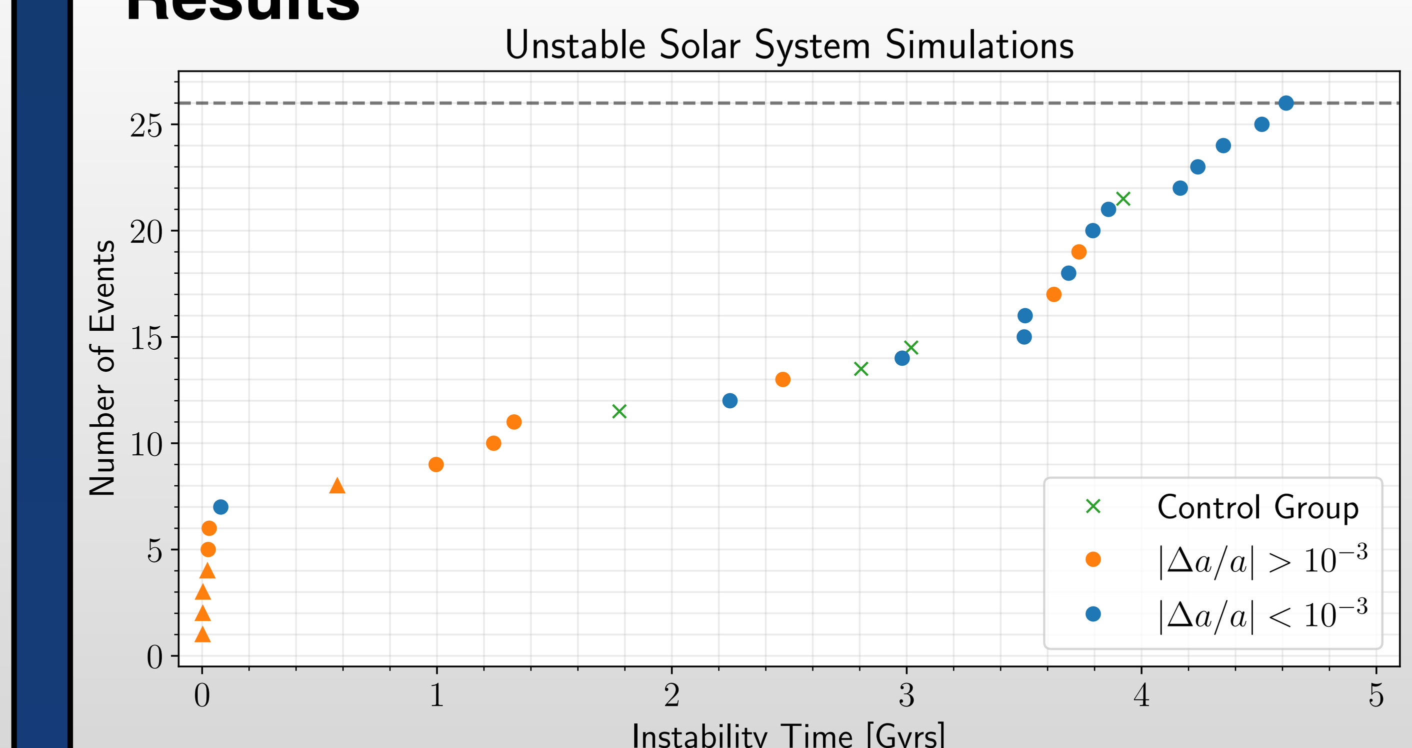
Conclusions

We have considered how weak perturbations from flyby scenarios increase the potential of destabilizing Mercury through secular interactions. We are able to describe how a relative perturbation to the semi-major axis of Neptune effects the secular modes of all the planets. For reference, Neptune would experience a relative perturbation of $|\Delta a/a| \sim 10^{-5}$ from a typical passing star in the local neighbourhood ($M_\star = 0.1\,M_\odot$, $V_\star = 40\,\mathrm{km/s}$) with a perihelion approach of $q_\star = 1000\,\mathrm{AU}$. We expect a perturbation of this strength to occur in the local neighbourhood about once every 5 Gyrs. With a 5σ significance we estimate a 1 in 20 chance that the Solar System will experience a critical perturbation event in the next 5 Gyrs, with a 23% chance of instability over the next 1 Gyr.

Methods

We integrated 2,880 simulations of the Solar System forward in time using REBOUND, with a REBOUNDx GR potential to correct for the additional perihelion precession. The Wisdom-Holman integrator with symplectic correctors and the lazy implementation of the kernel method was used to achieve highly accurate secular frequencies. We also used NASA JPL Horizons data starting at the J2000 epoch. We use a fixed timestep of $dt = 8.062$ days and integrated each simulation for 4.8 Gyrs. We divided the strength of stellar flybys into a control group, where perturbations are too small to be resolved from numerical noise, and experimental group, where perturbations range from numerical noise to so strong that close encounters and escapes occur quickly.

Results



This shows the total number of events that triggered the simulations to end before 4.8 Gyrs. Triangles indicate when the instability event was due to an escape rather than a collision.

For the control group, we found that 4 of the 960 simulations (0.42%) ended with Mercury-Venus collisions. For the experimental group, we found that 26 of the 1920 simulations (1.35%) ended in instability — 20 were Mercury-Venus collisions, one was an Earth-Mars collision, two resulted in a Uranus escape, two ended in a Neptune escape, and one finished with the escape of Mercury.

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