Shedding Light on the Eccentricity Valley:

Gap Heating and Eccentricity Excitation of Giant Planets in Protoplanetary Disks

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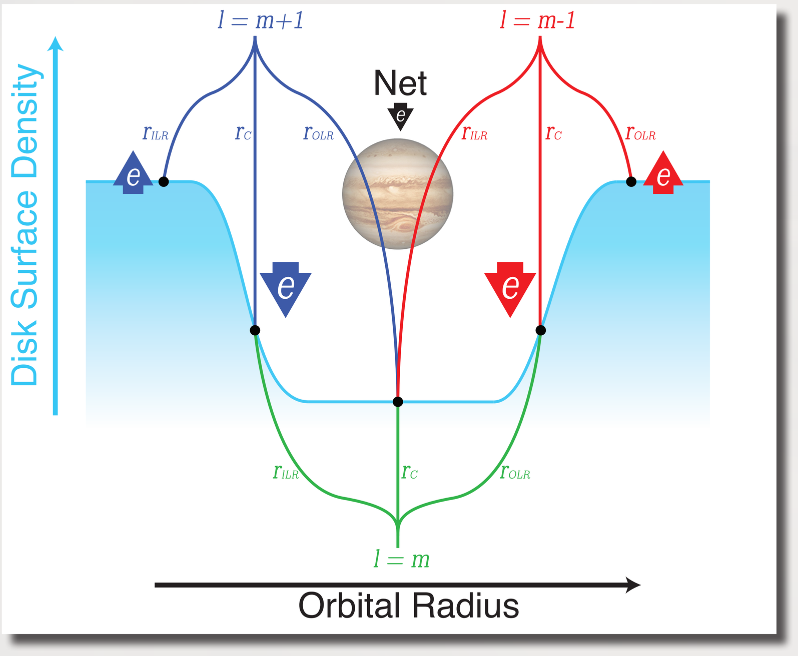
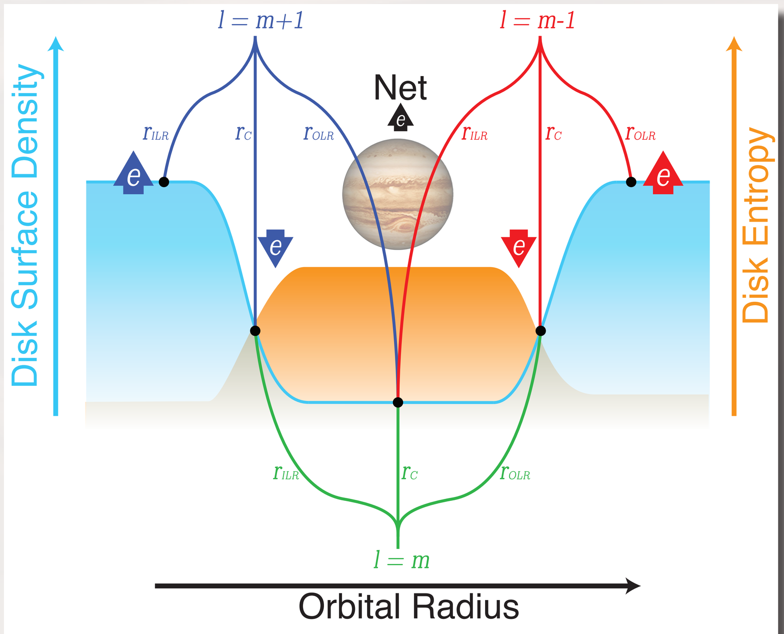
Eccentricity Damping and Excitation in Barotropic and Non-Barotropic Disks





When a giant planet clear a gap in the disk that surrounds it, the eccentricity evolution of the planet is dominated by the interaction at various resonances: the first order ($l=m\pm1$) outer and inner Lindblad Resonances (ILR, OLR), which excite eccentricity; and the first order ($l=m\pm1$) corotation resonances (C), which damp eccentricity.

In a **barotropic or isothermal disk** the corotation torque is proportional to the **gradient of the vortensity** $\zeta = \kappa^2/(2\Sigma\Omega)$, where κ is the epicyclic frequency, is the Ω orbital frequency, and Σ is the surface density of the disk. Goldreich and Sari (2003) showed that the corotation resonances that are located at the gap edge, where there is a steep density gradient that enhances the magnitude of corotation torque, dominate the evolution by only ~5% and cause **a net damping of planetary eccentricity**.

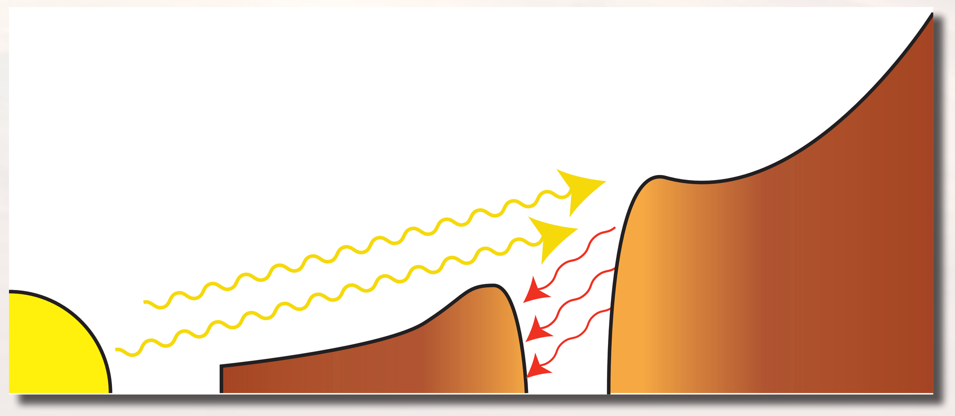
In **non-barotropic disks**, the disk is perturbed **adiabatically**, and in the presence of a radial **entropy gradient**, the corotation torques are modified by a baroclinic effect significantly, become instead proportional to **the gradient of the effective vortensity** $\zeta_{eff} = \kappa^2/(2\Sigma\Omega S^{1/\gamma})$, where S is the disk entropy and γ is the adiabatic index.

If the gap is heated, the entropy will rise inside the gap, where the density falls, reducing the corotation torque. If the entropy gradient is steep enough, this can allow the external Lindblad torques to dominate the eccentricity evolution, and **allow a net excitation of eccentricity.**

Thus, giant planets embedded in sufficiently heated gaps have their eccentricity pumped by the disk-planet interactions.

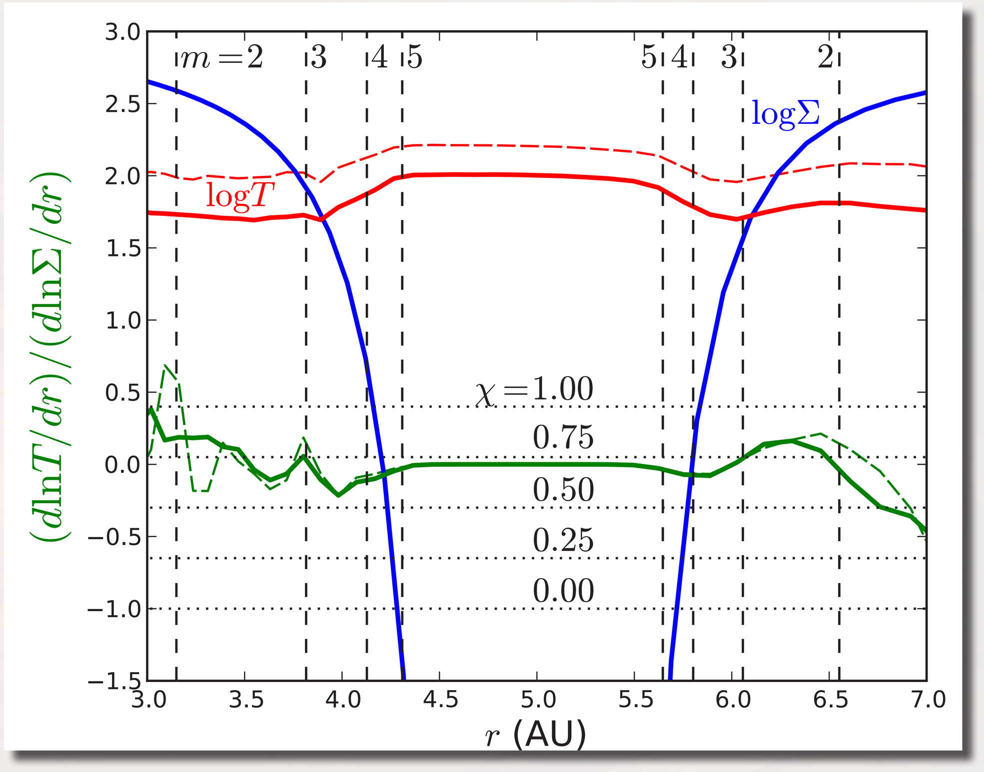
Gap Heating by Stellar Ilumination

Turner et al. (2012) showed that stellar illumination of a gap formed by a giant planet can signficantly modify the vertical structure and temperature profile at the gap and gap edges.



Light emitted from the star heats the disk, causing a flared shape (Chiang and Goldreich 1997). Because there is no material inside the gap to block the light, the outer rim of the gap is heated and puffs up, allowing it to receive more insolation, heating it even more. The gap edge re-radiates the energy (at lower energies) into the gap, heating both sides, until the gap reaches an equilibrium between heating by the star, and radiative cooling. If sufficient starlight strikes the outer rim of the gap, then the temperature in the gap can be raised significantly.

For an ideal gas $S \sim T\Sigma^{1-\gamma}$, and we can write the ratio of the non-barotropic to barotropic torque, $\chi \equiv \frac{\Gamma}{\Gamma_{bar}} = \frac{1}{\gamma} + \frac{1}{\gamma}\frac{d\ln T/dr}{d\ln \Sigma dr}$, in terms of the ratio of the logarithmic derivatives of temperature and density. If χ is below the critical value $\chi < \chi_{crit} \sim$ **0.95**, then eccentricity excitation can dominate.

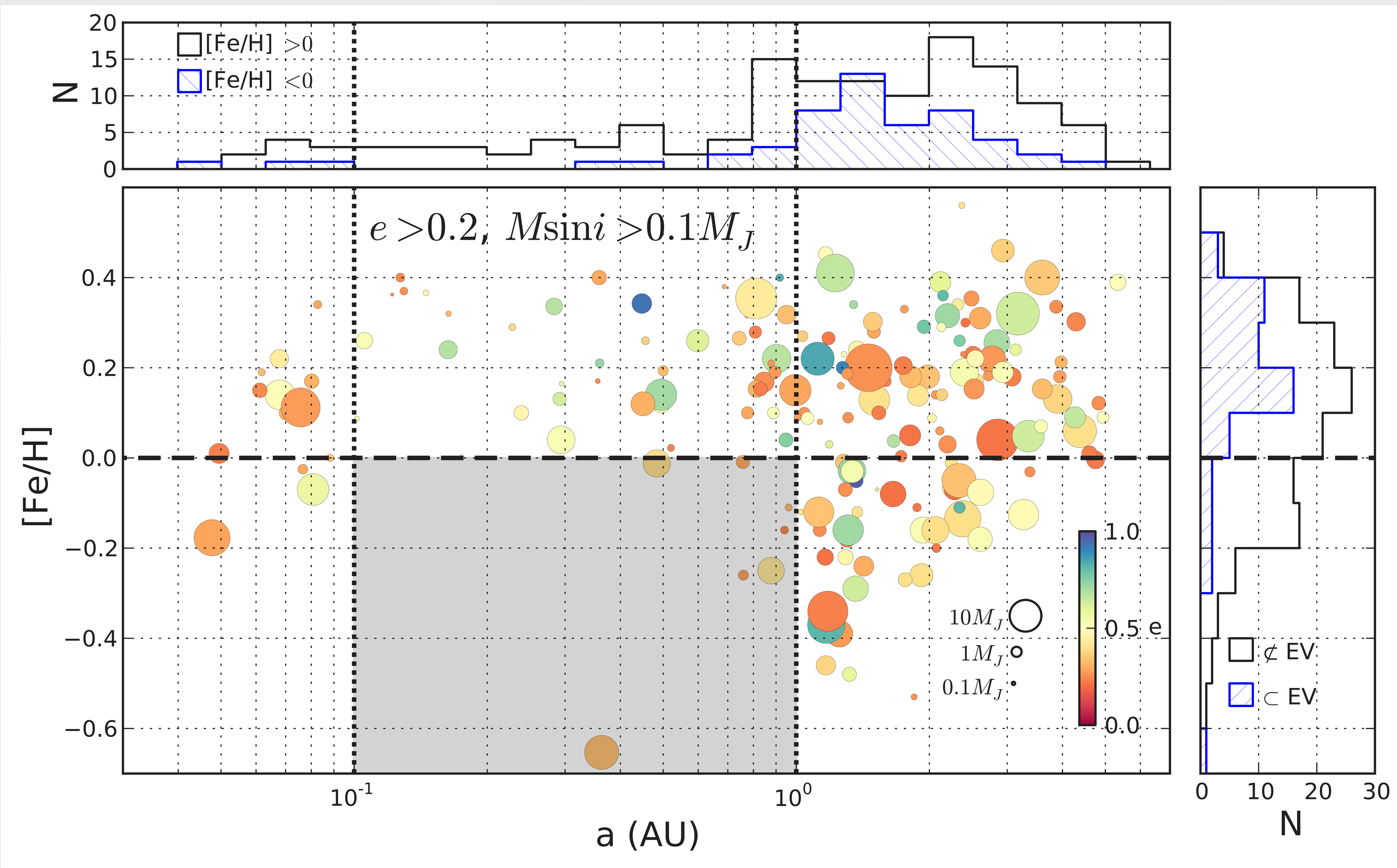


In the above Figure, we show this logarithmic derivative ratio (green) for the gap model from Turner et al. (2012), for a 1 M_J planet located 5 AU from a solar mass star with 1 solar luminosity (solid lines) and 10 solar luminosities (dashed lines). The surface density (blue) and temperature (red) profiles for the gap are also shown.

The corotation resonance locations are shown as vertical dashed lines for the first order m=2,3,4,5 resonances. The dashed lines correspond to values of $\frac{d\ln T/dr}{d\ln \Sigma dr}$ for various values of χ.

We see that the gap heating is sufficient to reduce the corotation torque by a factor of χ~0.75 at most resonances near the gap edges, allowing eccentricity excitation to occur.

The “Eccentricity Valley” for Metal-Poor Systems



Above we show data from the Exoplanet Orbit Database (Wright et al. 2011) illustrating the ``Eccentricity Valley'' for planets around low-metallicity stars, first identified by Dawson & Murray-Clay (2013). Here we have plotted the stellar metallicity, **[Fe/H]**, and semi-major axes, **a**, of all RV measured planets with $M \sin i > 0.1 M_J$ and eccentricity $e > 0.2$ that have metallicity measurements listed. The size of each circle is proportional to $M \sin i$, while the color corresponds to the eccentricity.

The ``Eccentricity Valley'' is the shaded region between 0.1 and 1 AU, where Dawson & Murray-Clay found a strong deficit of eccentric planets around metal-poor host stars.

In the upper histogram, the hatched blue region represents the number of low metallicity ([Fe/H] < 0) planets in a particular radius bin while the other solid white histogram is the number of high metallicity planets ([Fe/H] > 0).

For the right plot, the hatched blue histogram represents the number of planets inside the ``Eccentricity Valley'' (EV) region (0.1 AU < r < 1 AU) in a particular metallicity bin, while the solid white histogram represents the number of planets outside this region.

Dawson & Murray-Clay were able to reject with 99.14% confidence that the lack of high eccentricity planets in the ``Eccentricity Valley'' for metal poor stars is by chance.

As we have shown above, eccentricity can be generated for planets embedded in the disk through disk-planet interaction with insolation heated gaps. Something must prevent this from occurring inside the ``Eccentricity Valley'' region of metal-poor disks, where eccentricity damping occurs instead.

Self-Shadowing of T Tauri Disks By The Inner Dust Rim

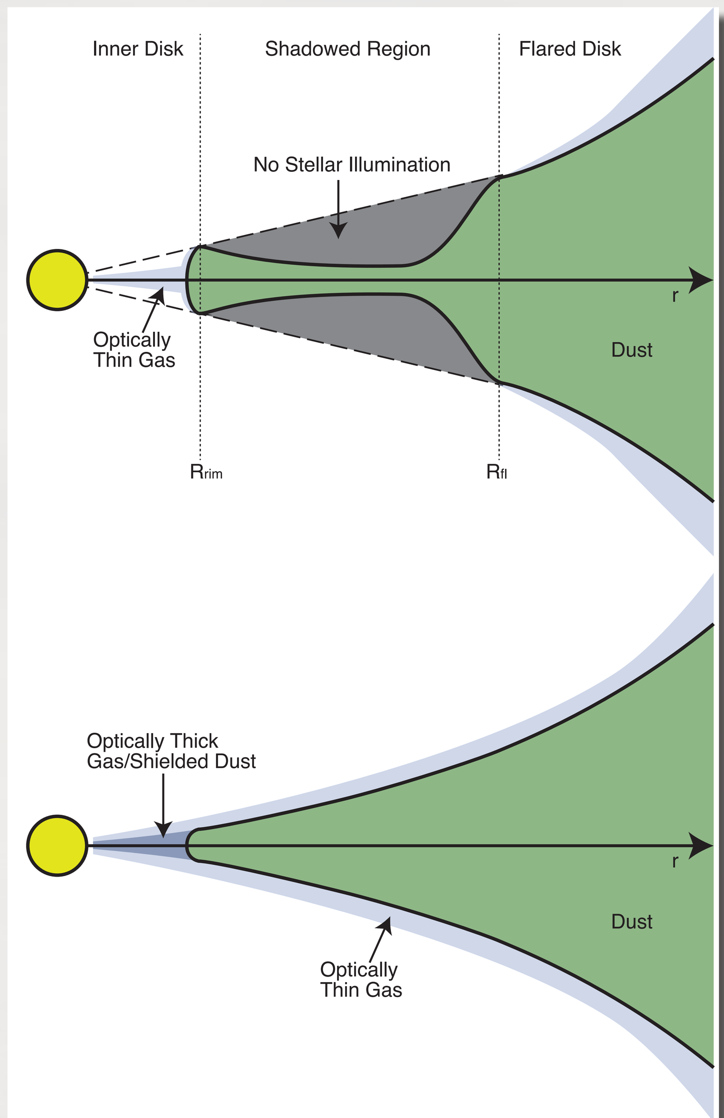
The progenitors of the solar mass stars studied by the RV sample in Figure to the left, are thought to be the classical T Tauri stars, which possess accretion disks from which planets will likely emerge. Muzerolle et al (2003) showed that in a significant fraction of such stars a near-infrared excess exists, which is fit well by a single blackbody at the dust sublimation temperature. This was found to be consistent with a dust rim (Dullemond et al., 2001) located at the dust sublimation radius.

Fitting this model, they found that if the gas interior to the dust sublimation radius is optically thin (see Muzerolle 2004), then the disk at the sublimation radius, located at $R_{rim} \sim$ **0.1AU** $(L_*/L_{sun})^{1/2}(T_d/1500\mathrm{K})^{-2}$, where T_d is the dust sublimation temperature, becomes puffed up as it receives insolation directly from the star, heating it far more than would be the case in a normal flared disk.

This raised optically thick rim blocks the starlight, and causes a shadowed region to form, where there is no direct stellar illumination of the disk, as shown schematically in the Figure to the right. **Without insolation to heat the gaps the entropy gradients are much less steep, and planets located in the shadowed region experience corotation torques similar to the barotropic levels, which result in a net eccentricity damping.**

The disk is again illuminated by the star at R_{fl}~10-20 R_{rim} (Dullemond et al., 2001) where it begins to flare, yielding **a range for the shadowed region of ~0.1 - 1 AU, where embedded planets have their eccentricity damped.**

The gas interior to the dust sublimation radius has opacity dominated by molecular lines (e.g. H2O) between ~1500K - 3000 (Eisner et al. 2009). Thus for higher metallicities (or accretion rates at the end of the disk era) the gas interior to the dust sublimation radius can become optically thick, preventing the direct insolation and puffing-up of the dust rim, and eliminating the shadowed region.



Such fully-illuminated disks can produce eccentric planets in the “Eccentricity Valley” region, as is seen for systems with **[Fe/H]>0.**

One might expect the extent of the shadowed region to decrease smoothly with increasing metallicity, as the height of the disk rim varies. Intriguingly, a hint of this may be present in the lower envelope of the planet distribution shown to the left.

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