Disk-Protoplanet Interactions

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Main Content:

- Solar System Forming Processes
- Surprising Observation
- Type I and Type II Migration

  Tidal interaction of a gaseous disk with a protoplanet
- Migration Terminated Mechanisms
- Migration Caused by Planetesimals

  Interaction of a planetesimal disk with a protoplanet

Solar System Forming Process

- Collapse of the nebula and formation of the protoplanetary disk and protosun.
- The fractionation of solids from the gaseous nebula, with the formation of planetesimals in a thin subdisk
- The accumulation of $O\left(10^3\right)$ km-sized protoplanetary embryos by binary accretion
- The ultimate combination of these embroys into planetary bodies. For giante planets, this also involves a substantial gas accretion phase as well.
- The solar wind of young Sun clears away the remaining gas. ($10^6 \sim 10^7$ y)

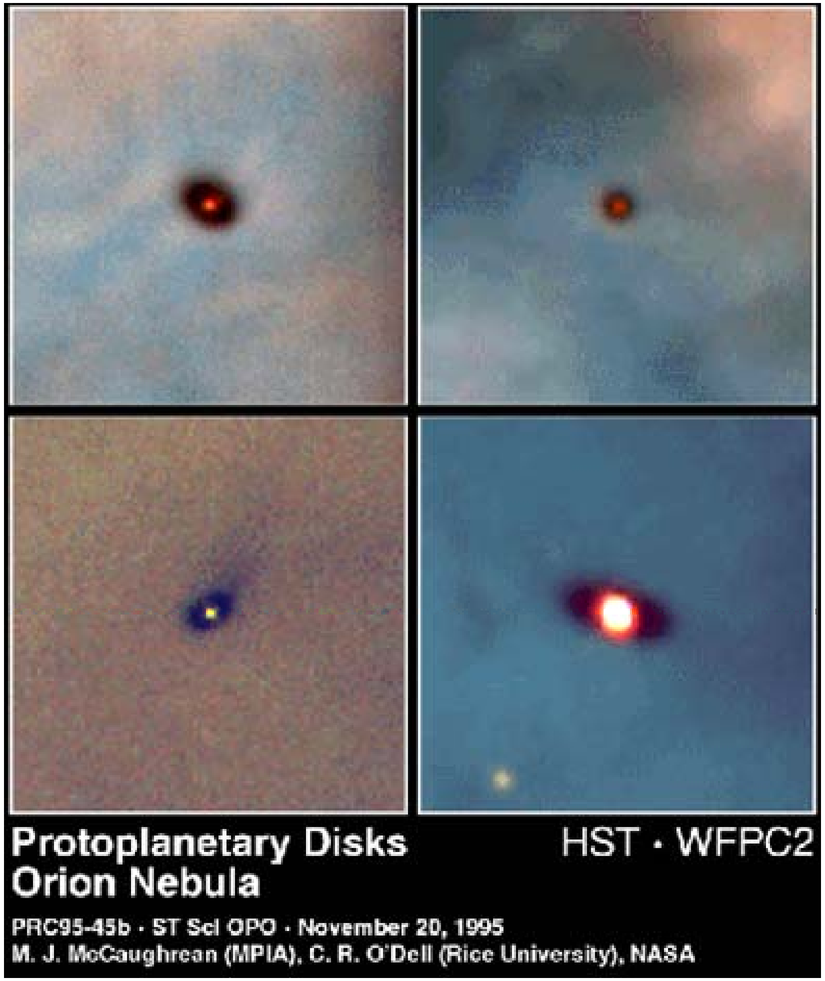
Protoplanetary Disks

Edge-On Protoplanetary Disk
Orion Nebula

HST • WFPC2

PRC95-45c • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

Protoplanetary Disks



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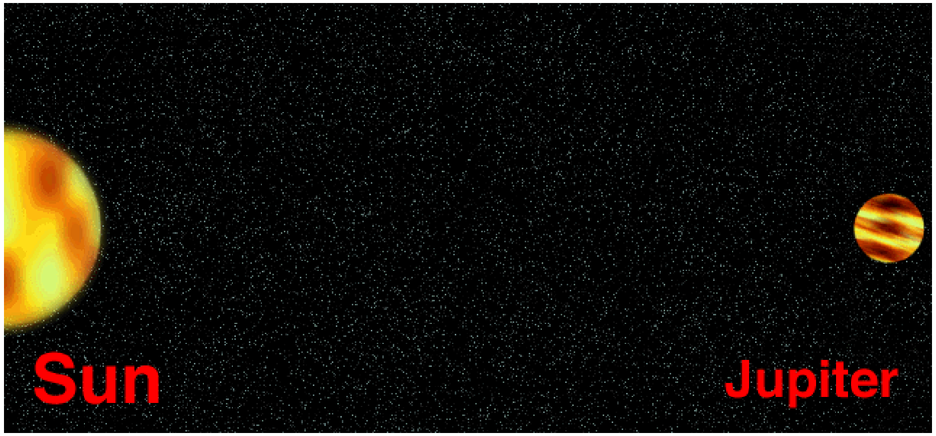
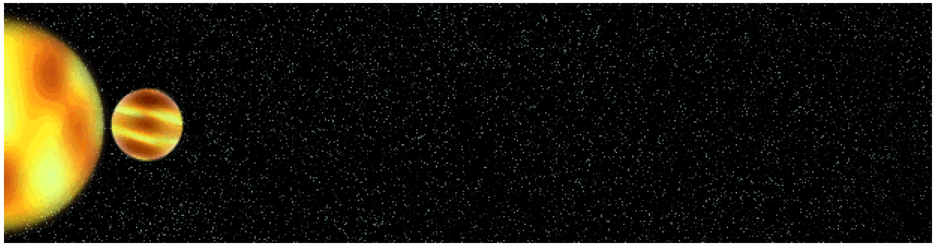
Surprising Observation

- (Mayer and Queloz 1995) The planetary companion orbiting the solar-type star 51 Pegasi has an approximately Jupiter Mass but occupies an orbit with semi-major axis of 0.05 AU (about seven stellar radii)





Why surprise? How to explain?

- The gas-giant close-in planet is unlikely to have formed at its present location.

  a) That location is too hot (2000 K) for the existence of any small solid particles;

  b) Escape speed is small in the early history of a planet, so evaporation mechanisms and ablation by the stellar wind will prevent the formation.

- BUT, once in place it can survive.
- SO, the planet probably formed at a much larger distance from the star (~5AU) and migrated inwards, then stopped in its present orbit.

Migration Mechanism:

Tidal Interaction with the gaseous disk.

- Lindblad Resonance (review)

  The figure of the potential rotates at steady pattern speed Ω_b, and κ_0 is the epicycle frequency.

  - **Corotation resonance**: $\Omega = \Omega_b$ the guiding center corotates with potential
  - **Lindblad resonance**: $m(\Omega - \Omega_b) = \pm\kappa$

    The protoplanet encounters successive crests of the potential at a frequency that coincides with the frequency of its natural radial oscillations. Radii at which such resonances occur are called **Lindblad radii**. The plus sign corresponds to the case in which the protoplanet overtakes the potantial, called the **inner Lindblad resonance.** The minus sign correspond to the crests of the potential sweep by the slowly rotating protoplanet, called the **outer Lindblad resonance**

The protoplanet of mass M, interacts with the disk at Lindblad resonance sites where the Doppler-shifted frequency of an *m*th-order term in its Fourier-expanded disturbing function matches the local natural oscillation frequency of the disk. i.e.

$$m(\Omega - \Omega_b) = \pm\kappa[1 + (mc/r\Omega)^2]^{1/2}$$

- Torque:

The attraction of the protoplanet for these nonaxisymmetric density perturbations results in the torque

$$T_m = \frac{\pi^2 m \sigma \psi_m^2}{r dD/dr}$$

Forcing function: $\psi_m = (r\phi_m + 2m\phi_m)\left[1 + 4(mc/r\Omega)^2\right]^{-1/2}$

Frequency distance: $D = \kappa^2 - m^2(\Omega - \Omega_s)^2 + (mc/r)^2$

Torque resonance: *D=0*

Surface Density

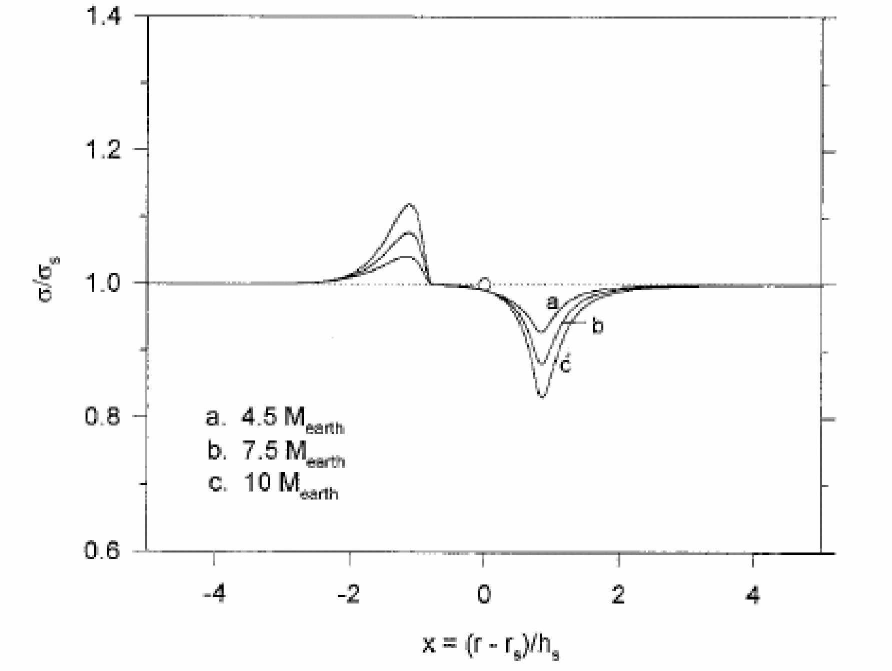


FIG. 1.—Surface density perturbations associated with type I drift of a protoplanet relative to a gas disk with $\alpha = 10^{-4}$. Motion is to the left; a density maximum leads the planet, and a density minimum trails it.

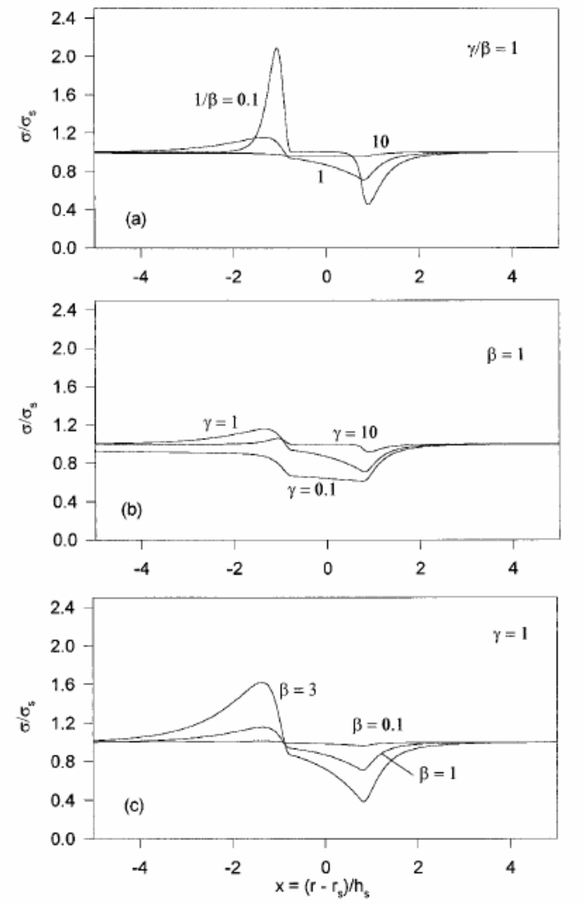


FIG. 11. Surface density perturbation for (a) constant mass and drift velocity, but increasing viscosity, (b) constant mass and viscosity, but increasing drift velocity, and (c) constant drift velocity and viscosity, but increasing mass. Distances are shown in units of scale height. Densities are normalized to unperturbed value.

(W.R.Ward, ApJ,482,211;ICARUS,126,261)

3D calculation

(M.R. Bate, S.H.Lubow G.I. Ogilvie and K.A.Miller, MNRAS, 341,213, 2003)

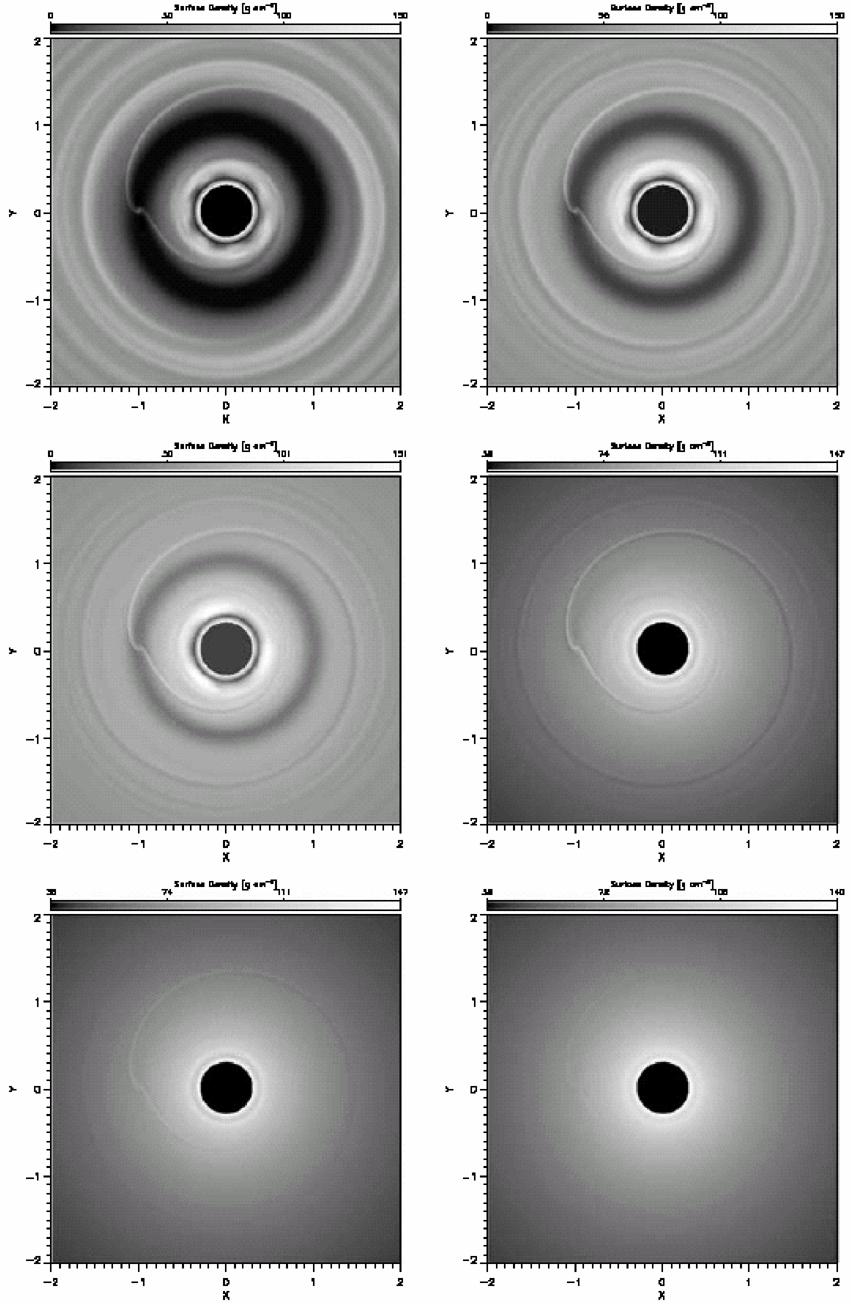


Figure 3. Disc surface densities, Σ, for planets with masses of 1, 0.3, 0.1, 0.03, 0.01 and 0.003 M_J (top-left to bottom-right).

Migration Type

Density wave torques repel material on either side of the protoplanet’s orbit and attempt to force open a gap in the disk.

- Type I: If the protoplanet is not large enough to open and sustain a gap, the net torque exerted on it by an undisturbed disk is not zero. The protoplanet drifts relative to disk material on a time scale inversely proportional to its mass. (Typical timescale: ~ 10^3 y for a Jupiter mass planet.)
- Type II: The protoplanet opens a gap in the disk that establishes a flow barrier to disk material. The protoplanet becomes locked to the disk and must ultimately share its fate. It’s drift rate is set by the viscousity. (Timescale: $10^5 \sim 10^6$ y or even longer)

Gap formation:

How massive should a planet be in order to open a gap?

The answer depend not only on the conditions in the nebula(surface density, temperature, viscosity) but also on the disipation mechanism of planet-induced density waves and the mobility of the planet.

With $\alpha < 10^{-3}$ (damping prescription is based on the weak nonlinear wave dissipation) In disks with Q (Toomre stability parameter) between ~30 and ~100 a gap is opened when the planetary mass reaches 2-15$M_{\oplus}$, depending on the disk viscosity and the planet’s location.

Drift velocity of Type I and Type II Migration

- Type I : (drift relative to the gas disk)

$$\frac{dr}{dt} \sim c_1 \left(\frac{M}{M_*}\right)\left(\frac{\sigma r^2}{M_*}\right)\left(\frac{r\Omega}{c}\right)^3 r\Omega$$

- Type II : (drift rate is set by the viscosity of the disk)

$$\frac{dr}{dt} \sim \left(\frac{\nu}{r}\right) \sim c_2 \alpha \left(\frac{c}{r\Omega}\right)^2 r\Omega$$

Transition from Type I to Type II

- Feedback Torque: produced by the disturbance
- Threshold mass: $$\frac{M_t}{M_*} \approx 2\alpha^{2/3}\left(\frac{M_t}{\sigma r^2}\right)^{1/3}\left(\frac{c}{r\Omega}\right)^3$$

  marks the point where the feedback torque rivals the background torque.
- As the threshold is exceeded, the motion fairly abruptly converts to the slower, locked (type II) mode.

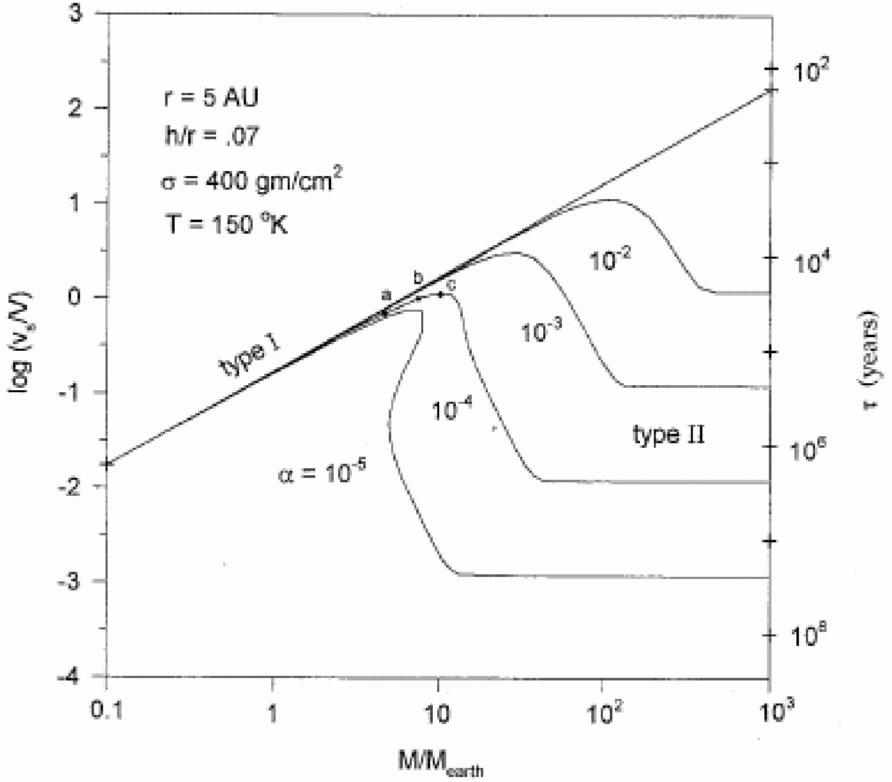


FIG. 2.—Drift velocity, $dr/dt = v_s$, as a function of mass for various values of the viscosity parameter. Velocities are normalized to $V = -2(M_\oplus/M_\odot)(\pi\sigma r^2/M_\odot)(r\Omega/c)^3 r\Omega$, where $M_\oplus = 6 \times 10^{27}$ g, i.e., an Earth mass. Assumed conditions are those considered appropriate for the Jovian zone in a minimum mass solar nebula. Transition from type I to type II motion is accompanied with a substantial drop in velocity. Characteristic orbital decay times, $\tau = r/v_s$, are shown on the right-hand scale.

(William R. Ward, ApJ,482,211,1997)

Migration Terminated Mechanisms:

- Mechanism 1: tidal interaction with the star

  If the young star is rotation rapidly enough that the co-rotation point was inside (0.05 AU). The tidal effect then result in outward migration. Balance point—Halted.

  Difficulty: 1.Temporary equilibrium; 2. Timescale

- Mechanism 2: truncation of the inner circumstellar disk by the stellar magnetosphere.

  Before reaching main sequence, tidal evolution timescale is larger than the stellar contraction timescale. After reaching main sequence, tidal migration timescale is larger than the age of the star.

Other Migration Mechanisms:

- Interactions between two or more Jupiter-mass planets. Main difficulty: low yield.
- The planet exchanges energy and angular momentum with the residual planetesimal disk through resonant gravitational interactions, graviational scattering, and physical collisions.

- ➢ $\Sigma > \Sigma_c$ Long-distance migration
- ➢ $\Sigma < \Sigma_c$ or most scattered planetesimals strike the star, migration halt
- ➢ $M_p < 3M_J$ Eccentricity of the planet’s orbit is reduced by the migration
- ➢ $M_p > 3M_J$ Eccentricity may increase

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