Critical Protoplanetary Core Masses in Protoplanetary Disks and the Formation of Short–Period Giant Planets

John C. B. Papaloizou1,2 and Caroline Terquem2,3,4

1Astronomy Unit, School of Mathematical Sciences, Queen Mary & Westfield College, Mile End Road, London E1 4NS, UK – J.C.B.Papaloizou@qmw.ac.uk
2Isaac Newton Institute for Mathematical Sciences, University of Cambridge, 20 Clarkson Road, Cambridge CB3 0EH, UK
3UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA – ct@ucolick.org
4On leave from: Laboratoire d’Astrophysique, Observatoire de Grenoble, Université Joseph Fourier/CNRS, BP 53, 38041 Grenoble Cedex 9, France

abstract

We study a solid protoplanetary core undergoing radial migration in a protoplanetary disk. We consider cores in the mass range $\sim 1 – 10 \, M_\oplus$ embedded in a gaseous protoplanetary disk at different radial locations.

We suppose the core luminosity is generated as a result of planetesimal accretion and calculate the structure of the gaseous envelope assuming hydrostatic and thermal equilibrium. This is a good approximation during the early growth of the core while its mass is less than the critical value, $M_{\text{crit}}$, above which such static solutions can no longer be obtained and rapid gas accretion begins. The critical value corresponds to the crossover mass above which rapid gas accretion begins in time dependent calculations.

We model the structure and evolution of the protoplanetary nebula as an accretion disk with constant $\alpha$. We present analytic fits for the steady state relation between disk surface density and mass accretion rate as a function of radius.

We calculate $M_{\text{crit}}$ as a function of radial location, gas accretion rate through the disk, and planetesimal accretion rate onto the core. For a fixed planetesimal accretion rate, $M_{\text{crit}}$ is found to increase inwards. On the other hand it decreases with the planetesimal accretion rate and hence the core luminosity.

We consider the planetesimal accretion rate onto cores migrating inwards in a characteristic time $\sim 10^3 – 10^5 \, \text{yr}$ at 1 AU as indicated by recent theoretical calculations. We find that the accretion rate is expected to be sufficient to prevent the attainment of $M_{\text{crit}}$ during the migration process if the core starts off significantly below it. Only at those small radii where local conditions are such that dust, and accordingly planetesimals, no longer exist can $M_{\text{crit}}$ be attained.

At small radii, the runaway gas accretion phase may become longer than the disk lifetime if the mass of the core is too small. However, within the context of our disk models, and if it is supposed that some process halts the migration, massive cores can be built–up through the merger of additional incoming cores on a timescale shorter than for in situ formation. A rapid gas accretion phase may thus begin without an earlier prolonged phase in which planetesimal accretion occurs at a reduced rate because of feeding zone depletion in the neighborhood of a fixed orbit.

Accordingly, we suggest that giant planets may begin to form through the above processes early in the life of the protostellar disk at small radii, on a timescale that may be significantly shorter than that derived for in situ formation.
Numerical calculations

Fits
$T_n=2519.74 \text{ K, } P_n=29466.3 \text{ cgs}$

$T_n=1968.16748 \text{ K, } P_n=18276.2773 \text{ cgs}$

$T_n=1428.76538 \text{ K, } P_n=1328.52039 \text{ cgs}$

$T_n=1063.53369 \text{ K, } P_n=42.190922 \text{ cgs}$

$T_n=728.176331 \text{ K, } P_n=6.651469 \text{ cgs}$

$T_n=140.046997 \text{ K, } P_n=0.131041 \text{ cgs}$

$T_n=0.05 \text{ AU}$

$T_n=0.06 \text{ AU}$

$T_n=0.15 \text{ AU}$

$T_n=0.5 \text{ AU}$

$T_n=1 \text{ AU}$

$T_n=5 \text{ AU}$
$t_{\text{mig}} = 2 \times 10^4$ yr
$M_{\text{pl}} = 1 \ M_{\odot}$
$\log_{10}(N_u)$

$r=r_2$

$r=r_1$

$y=x+c_1$ optically thin

$y=2x+c_2$ intermediate

$y=1.1x+c_3$ optically thick

$y=3.1x+c'$

$\log_{10}(\Sigma)$