Giant Planet Formation: episodic impacts vs. gradual core growth

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Outline

• Motivation:
  core growth by giant impacts important for giant planet formation?
• Methods
  impact modeling and numeric scheme
• Validation
• Results
• Conclusion
This model could be called the standard model and has been first worked out by Mizuno (1980, Progress of Theoretical Physics, 64, 544) and Bodenheimer & Pollack (1986, Icarus, 67, 391). It was refined in great detail by Pollack et al. (1996, Icarus, 124, 62) and extended recently by Alibert et al. (2004, AA, 434, 343).

In these models a solid core accretes first. Once this core reaches a critical mass (of order 10 Mearth) the gaseous envelope is accreted in a runaway process.
Motivation

• The planetesimal accretion rate is an important parameter in the core accretion scenario
• For numerical convenience, formation models use gradual core growth modelled by a rate equation
• However, in the oligarchic growth regime, possibly:
  ‣ the core growth is dominated by large impacts
  ‣ the mass ratio is large, e.g. 0.1

Does this change the current picture of giant planet growth?
Methods
Procedure

• Replace constant $dM_z/dt$ with „impacts“
• Impacts are modelled as Gaussian $dM_z/dt$ curve: width gives timescale
• Parameters:
  ‣ impact mass
  ‣ impact timescale
  ‣ (initial & background rate)
• Study thermal response on impact
impact model

core growth rate

parameters:
• impact mass
• impact timescale

\[ \tau_{EW} = \sigma \sqrt{2\pi} \]

impact vs. continuous episodic vs. gradual
when same mass accreted: stop accretion and compare

0.02 Me in $10^3$ yr

dM/dt [Me/yr]

time [Ma]
core growth rate log scale

- **impact**
- 1 Me in $10^4$ yr
- initial model from continuous accretion
- comparison: continue continuous accretion
- at minimum rate until same mass accreted

$$\frac{dM_z}{dt} \text{[Me/yr]}$$

- time [Ma]

Christopher Broeg
Dienstag, 12. Oktober 2010
Calculation

- Henyey type code with self-adaptive 1D grid
- Stellar structure equations
- Quasi-hydrostatic equilibrium
- Impact timescale $t_{\text{imp}}$: $t_{\text{dyn}} \ll t_{\text{imp}} \ll t_{\text{KH}}$
- Neglect energy deposition in atmosphere
- Material
  - Saumon et al. (1995) EOS
code verification
Verification: Jupiter formation (Pollack J1)

- **Model**
  - feeding zone: left and right of planet
  - give $\Sigma_0$
  - no migration

- **Simplifications / differences:**
  - capture radius = core radius
  - feeding zone width = 4 hill radii
  - const. grav. focussing: $F_g = 10^5$
  - outer BC: hill radius

- **Maximum gas accretion rate** $10^{-4} \, M_e/yr$
time [Ma]

luminosity [L⊙]

Pollack J1, 15
In this case, the planet is located at 1 AU, the initial surface density of the protoplanetary disk is $\rho_0 = 10^{-7} \text{g/cm}^2$, and planetesimals that dissolve during their journey through the planet's envelope are allowed to sink to the planet's core. Other parameters are listed in Table III. The solid line represents accumulated solid mass, the dotted line accumulated gas mass, and the dot–dashed line the planet's total mass. The planet's growth occurs in three fairly well-defined stages. During the first $F$ years, the planet accumulates solids by rapid runaway accretion. This ''phase $F$'' ends when the planet has severely depleted its feeding zone of planetesimals. The accretion rates of gas and solids are nearly constant with $\dot{M}_g = \dot{M}_s$ during most of the $S$ years' duration of phase $S$. The planet's growth accelerates toward the end of phase $S$, and runaway accumulation of gas and, to a lesser extent, solid, characterizes phase $d$. The simulation is stopped when accretion becomes so rapid that our model breaks down. The endpoint is thus an artifact of our technique and should not be interpreted as an estimate of the planet's final mass.

Logarithm of the mass accretion rates of planetesimals (solid line) and gas (dotted line) for case $J1$. Note that the initial accretion rate of gas is extremely slow, but that its value increases rapidly during phase $F$ and early phase $S$. The small-scale structure which is particularly prominent during phase $F$ is an artifact produced by our method of computation of the added gas mass from the solar nebula.

Luminosity of the protoplanet as a function of time for case $J1$. Note the strong correlation between luminosity and accretion rate.

Surface density of planetesimals in the feeding zone as a function of time for case $J1$. Planetesimals become substantially depleted within the planet's accretion zone during the latter part of phase $F$, and the local surface density of planetesimals remains small throughout phase $S$.

Four measures of the radius of the growing planetary embryo in case $J1$. The solid curve shows the radius of the planet's core, $R_{\text{core}}$, assuming all accreted planetesimals settle down to this core. The dashed curve represents the effective capture radius for planetesimals of $R_s$ km in radius, $R_c$. The dotted line shows the outer boundary of the gaseous envelope at the ''end'' of a timestep, $R_p$. The long- and short-dashed curve represents the planet's accretion radius, $R_a$.

If this simulation had been done in a gas-free environment, however, it is possible to carry our simulations of the formation of the giant planets to a reasonable endpoint, as might be appropriate for the formation of the terrestrial planets, then the next phase would have to involve interacting embryos for accretion to reach the desired culmination point (Lissauer 1996).
Verification summary

• Good agreement with Pollack
• \( L_{\text{max}} = 10^{-5} L_{\text{sun}} \)
  \( (10^{-3} \text{ when limiting accretion to } 0.01 \text{ instead of } 10^{-4} \text{ Me/yr}) \)
• Jupiter values at 4.5 Gyr:
  ‣ Mass: 1.008 Mjup (by construction)
  ‣ Radius (4.5 Ga) = 1.03 R_{Jup}
  ‣ \( M_z = 34 M_{\text{earth}} \)
  ‣ \( L = 0.76 L_{\text{jup internal}} \)
• Mach number of inflow: -0.4
• Further tests:
  ‣ static (Mizuno 1980),
  ‣ CoRoT-9b,
  ‣ HD209458b (all verification successful)
Results:
impact vs gradual growth

• 1 example case: 1 M$_e$ impact on 10 M$_e$ target core
  envelope mass, gas accretion rate, luminosity
• all targets for 1 M$_e$ impact
Scenario

- Growing proto-planet core at 3 AU in MMSN, solar host star
- Nominal core accretion rate: $10^{-6}$ Earth masses / yr
- At desired impact core mass:
  - impact followed by no solid accretion
  - compare to gradually growing case
- Parameter study:
  - different impact masses 0.02, 0.1, 0.5, and 1 Earth masses
  - different target masses $M_c=1,2,3,\ldots,15$ Earth masses
envelope mass (impact 1 on 10 $M_e$)

sequence:
1. gas ejection
2. fast accretion
3. gas replenished after 0.055 Myr
4. gas accretion slows down

$\Rightarrow$ net more gas accreted
gas accretion rate

dM_{env}/dt [M_⊕/Myr] vs. time [Myr]
gas accretion rate

- larger accretion rate at end
- caused by lack of solid accretion
- all solid accretion finished with impact
luminosity

- Impact energy removed
- Additional energy from gas accretion
- Negative
10 $M_e$ target, 1 $M_e$ impact

Mod.Nr=1

time [Ma]

Envelope Mass / [kg]

Pressure / [Pa]

Temperature / [K]

Luminosity / [W]

Radius / [m]
envelope mass during 1 $M_e$ impact
envelope mass during 0.1 M_e impact
envelope mass after 1 $M_e$ impact

time [Myr]

envelope mass [$M_\oplus$]
luminosity evolution 1 M_e impacts

core luminosity  luminosity
ejected envelope mass as a function of target size for 4 different impact sizes

- Insufficient energy to remove envelope
- More than enough energy to remove envelope
- 100% efficiency

- Larger cores: insufficient energy to remove envelope
- Smaller cores: more than enough energy to remove envelope

- Energy impact / total binding energy

- Envelope mass ejected / envelope mass
envelope accretion rate: ratio episodic vs continuous

**(Corrected y-axis label from talk)**

- **E imp 1.0**
- **E imp 0.5**
- **E imp 0.1**
- **E imp 0.02**

Triggered runaway accretion

Insufficient energy
Discussion

• Results show that the impact scenario yields more massive envelopes compared to gradual core growth.
• Most of the energy can be transported at very high luminosity immediately after envelope ejection.
• The Kelvin-Helmholtz timescale becomes very small during the impact and the energy from solid accretion can be shed quickly (For a $10 \, M_e$ core: before: 0.2 Myr; during: 200 yr; after: 1.6 Myr).
• The subsequent phase without solid accretion quickly accumulates a large envelope.
comparison with stopped core accretion
impact accretion vs. no accretion

![Graph showing impact accretion vs. no accretion.

- Core accretion stop
- Impact
- Gradual accretion
- Beyond t_{\text{comp}}

Summary & Conclusion

• We were able to calculate episodic large impacts in the quasihydrostatic approximation
• Results show that the impact scenario yields more massive envelopes compared to the gradual core growth
• The impact itself leads to a very rapid loss of the deposited energy
• Gas accretion as fast as the shut-off case with the larger (post-impact) core
• In the oligarchic growth regime, this effect can be very important
• With this method, formerly sub-critical cores can accrete large amounts of gas

Broeg & Benz 2010, in prep.