Global simulations of protoplanetary discs with Ohmic resistivity and ambipolar diffusion

Oliver Gressel
Niels Bohr International Academy (NBIA), Copenhagen

Richard P. Nelson (QMUL, London)
Neal J. Turner (JPL-Caltech, Pasadena)
Colin P. McNally (NBIA, Copenhagen)
Udo Ziegler (AIP, Potsdam)

August 04-08, 2014
“Non-ideal MHD, Stability, and Dissipation in Protoplanetary Disks”
Motivation: formation of gas-giant planets

Effects of additional microphysics

schematics of protostellar disc

Armitage (2011)
Motivation: formation of gas-giant planets
Effects of additional microphysics

embedded sub-disc

isothermal HD  non-isoth. HD  non-isoth. MHD
embedded sub-disc

![Graph showing log $\rho$ vs. height and radius with color bars for isothermal HD, non-isoth. HD, and non-isoth. MHD.](image-url)
Motivation: formation of gas-giant planets
Effects of additional microphysics

embedded sub-disc

\[ \log \rho \left[ \text{g cm}^{-3} \right] \]

-13.0 -12.5 -12.0 -11.5 -11.0 -10.5 -10.0

\[ \log \rho \left[ \text{g cm}^{-3} \right] \]

-16 -15 -14 -13 -12 -11 -10

isothermal HD  non-isoth. HD  non-isoth. MHD
variability of circumplanetary disc

![Image showing variability of circumplanetary disc at different times](image-url)
Motivation: formation of gas-giant planets
Effects of additional microphysics

circum-jovian jet

Gressel et al. (2013), predicted by Quillen & Trilling (1998) and Fendt (2003), also cf. Machida et al. (2006)
Motivation: formation of gas-giant planets
Effects of additional microphysics

revised schematics of protostellar disc

Motivation: formation of gas-giant planets
Effects of additional microphysics

adding ambipolar diffusion

- external ionisation via X-Rays, CRs, **new**: FUV layer
- Ohmic resistivity, **new**: ambipolar diffusion
- (no) magnetorotational instability (MRI)
  $\rightarrow$ (no) turbulent surface layers
- magneto-centrifugal (laminar) disc winds
- effect of reduced gas column in the gap region
- ionisation state of the CPD
- effect on jet launching

Magneto-centrifugal wind from PPD with AD

O. Gressel
2014-08-04 – Non-ideal MHD in PPDs
Motivation: formation of gas-giant planets
Effects of additional microphysics

adding ambipolar diffusion

- external ionisation via X-Rays, CRs, new: FUV layer
- Ohmic resistivity, new: ambipolar diffusion
- (no) magnetorotational instability (MRI)
  → (no) turbulent surface layers
- magneto-centrifugal (laminar) disc winds

- effect of reduced gas column in the gap region
- ionisation state of the CPD
- effect on jet launching

magneto-centrifugal wind from PPD with AD
Motivation: formation of gas-giant planets
Effects of additional microphysics

The fiducial model

\[ \beta_p^0 = 10^5, \quad \text{d/g mass ratio} \times 10^{-3}, \quad \text{XR+CR+FUV} \]

- MMSN disc model, NVF with midplane
Motivation: formation of gas-giant planets

Effects of additional microphysics

The fiducial model

- MMSN disc model, NVF with midplane $\beta_{p0} = 10^5$, $d/g$ mass ratio $10^{-3}$, XR+CR+FUV
Motivation: formation of gas-giant planets
Effects of additional microphysics

the fiducial model

MMSN disc model, NVF with midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
Motivation: formation of gas-giant planets
Effects of additional microphysics

The fiducial model

- MMSN disc model, NVF with midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
the fiducial model

- MMSN disc model, NVF with midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
Motivation: formation of gas-giant planets
Effects of additional microphysics

**collisional ionisation of inner disc**

- MMSN disc model, midplane $\beta_p 0 = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV + thermal
- puffed-up turbulent disc shadows FUV radiation $\rightarrow$ variability/intermittency of disc wind
Motivation: formation of gas-giant planets
Effects of additional microphysics

Collisional ionisation of inner disc

- MMSN disc model, midplane $\beta_p 0 = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV + thermal
- Puffed-up turbulent disc shadows FUV radiation $\rightarrow$ variability/intermittency of disc wind
stability of current sheets

flaring MMSN disc model, midplane $\beta_p = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
stability of current sheets

flaring MMSN disc model, midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
Motivation: formation of gas-giant planets

Effects of additional microphysics

stability of current sheets

flaring MMSN disc model, midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
Motivation: formation of gas-giant planets
Effects of additional microphysics

non-axisymmetric evolution

(flaring) MMSN disc with AD+Ohm

MMSN with Ohmic resistivity alone

\[ \beta_{p0} = 10^5, \text{ d/g mass ratio } 10^{-3}, \text{ XR+CR+FUV} \]
Motivation: formation of gas-giant planets
Effects of additional microphysics

**non-axisymmetric evolution**

(flaring) MMSN disc with AD+Ohm

MMSN with Ohmic resistivity alone

- flaring MMSN disc model, midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-3}$, XR+CR+FUV
Motivation: formation of gas-giant planets
Effects of additional microphysics

**reduced dust fraction**

- MMSN disc model, midplane $\beta_{p0} = 10^5$, d/g mass ratio $10^{-4}$, XR+CR+FUV
shear-layer instability

- velocity shear-layer at FUV transition – also seen in Bai & Stone (2013)
- most probably distinct from Moll (2012) “clumping” instability
- → coincidence of FUV transition and wind base, yes or no?!
- → need to control tapering of FUV transition?!
Motivation: formation of gas-giant planets
Effects of additional microphysics

**shear-layer instability**

- velocity shear-layer at FUV transition – also seen in Bai & Stone (2013)
- most probably distinct from Moll (2012) “clumping” instability
- → coincidence of FUV transition and wind base, yes or no?!
- → need to control tapering of FUV transition?!
shear-layer instability

- velocity shear-layer at FUV transition – also seen in Bai & Stone (2013)
- most probably distinct from Moll (2012) “clumping” instability
- $\Rightarrow$ coincidence of FUV transition and wind base, yes or no?!
- $\Rightarrow$ need to control tapering of FUV transition?!
shear-layer instability

- velocity shear-layer at FUV transition – also seen in Bai & Stone (2013)
- most probably distinct from Moll (2012) “clumping” instability
- → coincidence of FUV transition and wind base, yes or no?!
- → need to control tapering of FUV transition?!
**Table 2. Summary of simulation results.**

<table>
<thead>
<tr>
<th></th>
<th>(z_b)</th>
<th>(z_A)</th>
<th>(T_{Re}^{\phi})</th>
<th>(T_{Maxw}^{\phi})</th>
<th>(T_{Maxw}^{\phi})</th>
<th>(M_{wind})</th>
<th>(M_{accr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-b6</td>
<td>—</td>
<td>7.60 ± 0.45</td>
<td>6.87 ± 14.4</td>
<td>7.44 ± 0.95</td>
<td>—</td>
<td>1.47 ± 0.37</td>
<td>0.14 ± 1.53</td>
</tr>
<tr>
<td>OA-b5</td>
<td>5.23 ± 0.07</td>
<td>7.31 ± 0.17</td>
<td>3.63 ± 0.19</td>
<td>2.22 ± 0.06</td>
<td>9.82 ± 0.08</td>
<td>0.78 ± 0.01</td>
<td>0.43 ± 0.01</td>
</tr>
<tr>
<td>OA-b6</td>
<td>7.22 ± 0.48</td>
<td>6.94 ± 0.37</td>
<td>0.21 ± 0.18</td>
<td>0.79 ± 0.06</td>
<td>0.58 ± 0.06</td>
<td>0.36 ± 0.03</td>
<td>0.08 ± 0.02</td>
</tr>
<tr>
<td>OA-b7</td>
<td>7.31 ± 0.70</td>
<td>6.39 ± 0.16</td>
<td>0.07 ± 0.13</td>
<td>&lt; 0.01</td>
<td>0.22 ± 0.01</td>
<td>0.03 ± 0.01</td>
<td>0.00 ± 0.03</td>
</tr>
<tr>
<td>OA-b5-d4</td>
<td>5.27 ± 0.07</td>
<td>7.33 ± 0.18</td>
<td>0.11 ± 0.30</td>
<td>2.88 ± 0.11</td>
<td>9.88 ± 0.12</td>
<td>0.75 ± 0.01</td>
<td>0.33 ± 0.04</td>
</tr>
<tr>
<td>OA-b5-flr</td>
<td>4.81 ± 0.03</td>
<td>6.90 ± 0.31</td>
<td>0.26 ± 0.21</td>
<td>1.78 ± 0.02</td>
<td>14.3 ± 0.02</td>
<td>1.44 ± 0.01</td>
<td>0.64 ± 0.02</td>
</tr>
<tr>
<td>OA-b5-flr-nx</td>
<td>4.78 ± 0.03</td>
<td>7.50 ± 0.30</td>
<td>2.28 ± 9.24</td>
<td>1.87 ± 0.04</td>
<td>13.0 ± 0.04</td>
<td>1.31 ± 0.01</td>
<td>0.64 ± 0.03</td>
</tr>
<tr>
<td>OA-b5-nx</td>
<td>5.10 ± 0.04</td>
<td>7.34 ± 0.13</td>
<td>0.94 ± 9.29</td>
<td>1.89 ± 0.06</td>
<td>7.84 ± 0.02</td>
<td>0.66 ± 0.01</td>
<td>0.29 ± 0.03</td>
</tr>
</tbody>
</table>

The vertical position of the base of the wind, \(z_b\), and the Alfvén point, \(z_A\), are found independent on the radial location when measured in local scale heights, \(H\). The viscous accretion stresses \(T_{Re}^{\phi}\) are vertically integrated within \(|z| \leq z_b\) – note the different units for Reynolds and Maxwell stresses. The wind stress, \(T_{z\phi}\), is inferred at \(z = \pm z_b\). All stresses depend weakly on radius; listed values are at \(r = 3\) au.
summary of results

- First stratified global simulations of PPDs with Ohm+AD
  - proper wind geometry is naturally obtained
  - mass-loss rates agree with expectations from observations

- Long-term evolution and secondary instabilities
  - strong current sheets form adjacent to “un-dead” field belts
  - current layers break-up via tearing-mode (?!?) instability
  - FUV transition drives (KH-unstable) velocity shear layer

- Future prospects
  - study time-variability induced by MRI-active inner disc
  - understand dependence of wind solution on input parameters
  - effect of AD within gap region / CPD evolution / core accretion
  - inclusion of Hall term / ...