Low energy protostellar cosmic rays in protoplanetary disks

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Accretion/Outflow workshop, ESTEC, Noordwijk 29th Oct 2015

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Angular Momentum Transport

Two main options if the mechanism is magnetic:

Magnetorotational instability
(Balbus & Hawley 1991)

Magnetocentrifugally launched winds
(Blandford & Payne 1982)

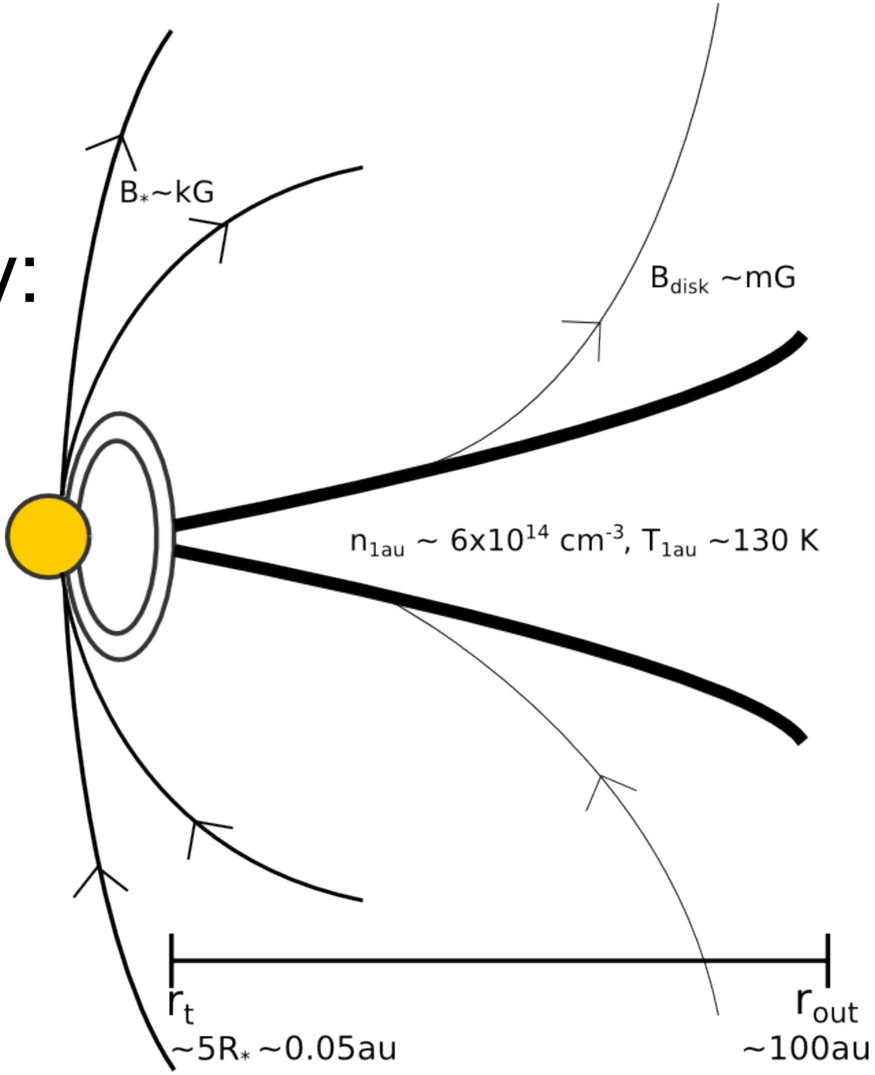
Both require a certain level of ionisation

Sources of Ionisation

PPDs are *weakly ionised* by:

- Stellar x-rays/FUV
- Radioactivity
- Cosmic rays -

Galactic vs. protostellar



Recent clues...

Observational:

- Ceccarelli et al. (2014) - *Herschel* observations
- Ainsworth et al. (2014) - Bow shock of DG Tau

Theoretical:

- Cleeves et al. (2014) - exclusion of galactic CRs
- Padovani et al. (2015) - Acceleration sites
- Turner & Drake (2009) - Modelling of CRs

Cosmic ray density from the protostar

Solar x-ray luminosity: $L_\odot^{\rm X} \sim 5 \times 10^{27} {\rm erg/s}$

(Peres et al 2002)

Solar cosmic rays (solar wind):

$$L_\odot^{\rm CR} \sim L_\odot^{\rm SW} \sim 1 \times 10^{27} {\rm erg/s}$$

YSOs are more magnetically active

(Feigelson & Montemerle 1999) $L_*^{\rm X} \sim 1 \times 10^{29} {\rm erg/s}$

$$L_*^{\rm CR} \sim L_\odot^{\rm CR} \frac{L_*^{\rm X}}{L_\odot^{\rm X}} \sim 1 \times 10^{28} {\rm erg/s}$$

How to model cosmic rays

Propagation of cosmic rays:

- Can be treated as a diffusive process
- Simplest analytic model gives $\sim \frac{1}{r}$ distribution

X-rays give $\sim \frac{1}{r^2}$ distribution

CRs: More effective ionisation at large radii

Sites of acceleration: Inner edge of accretion disk, accretion shock, knots in jets...

Formulation + diffusion equation

Calculate for GeV particles (minimally ionising but very abundant):

$$\frac{\partial n_{\mathrm{CR}}(r,z)}{\partial t} = \nabla(D(r,z)\nabla n_{\mathrm{CR}}) - \frac{1}{\tau(r,z)} n_{\mathrm{CR}}$$

$D(r,z)$ - diffusion coefficient; $\tau(r,z)$ - sink term

[Inhomogeneous but isotropic]

$$D \propto \left(\frac{\delta B}{B}\right)^2 R_{\mathrm{L}}(\lambda) \qquad \frac{1}{\tau(r,z)} \propto \rho(r,z)$$

Formulation + diffusion equation

Steady-state

$$\frac{\partial n_{\rm CR}(r,z)}{\partial t} = \nabla(D(r,z)\nabla n_{\rm CR}) - \frac{1}{\tau(r,z)} n_{\rm CR}$$

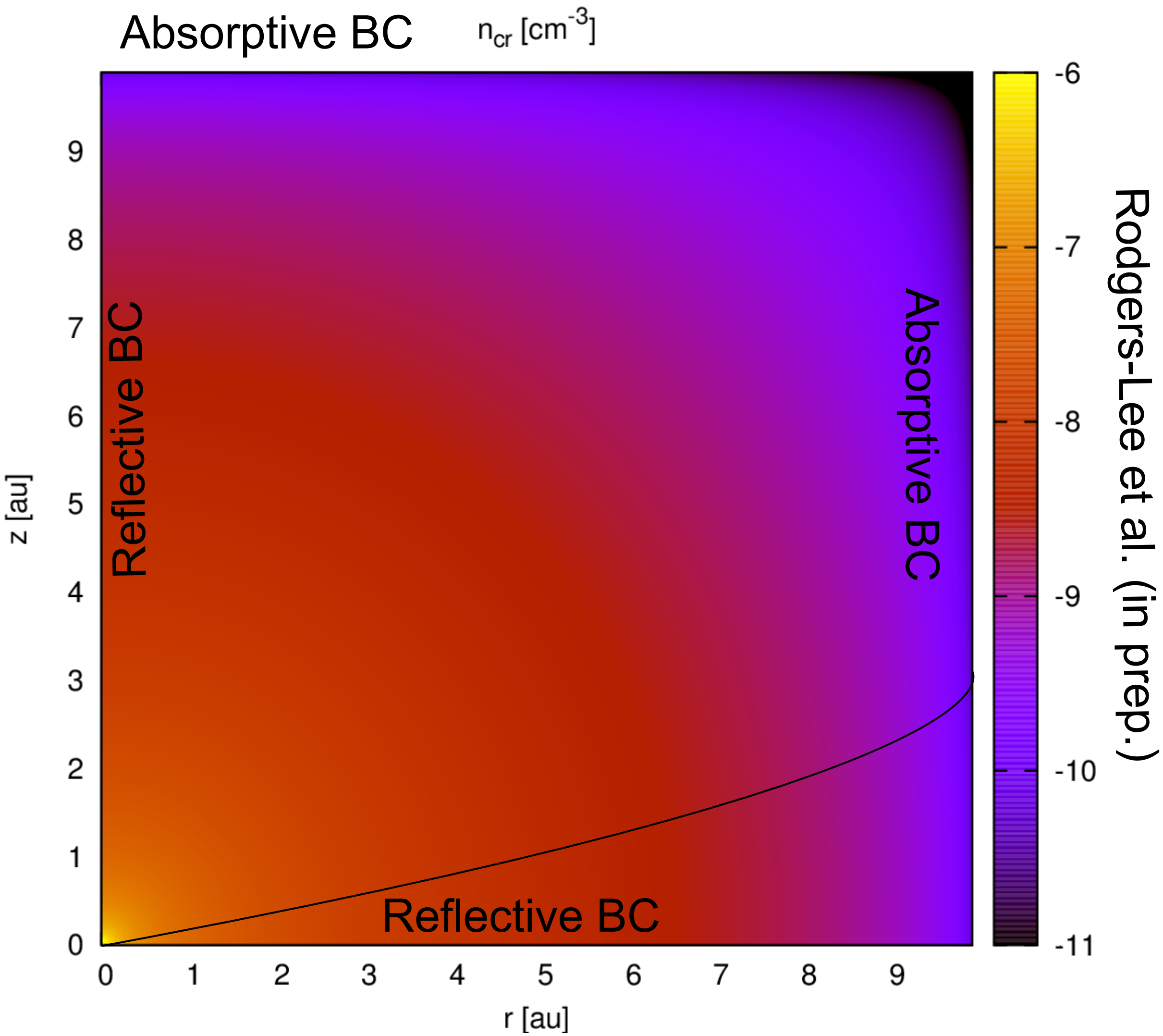
$D(r,z)$ - diffusion coefficient; $\tau(r,z)$ - sink term

[Inhomogeneous but isotropic]

$$D \propto \left(\frac{\delta B}{B}\right)^2 R_{\rm L}(\lambda) \qquad \frac{1}{\tau(r,z)} \propto \rho(r,z)$$

GeV particle in mG ~ 10^{-4} au

Results: Cosmic ray densities



Source of CRs at 0.05au

2D axisymmetric

$$D = 0.02$$

$$\frac{1}{\tau(r,z)} \propto \rho(r,z)$$

$$\rho(r,z) = \rho_0 e^{-r_{\rm in}^2/r^2} \left(\frac{r_0}{r}\right)^q e^{-z^2/2H^2} + \rho_{\rm ISM}$$

Results: $n_{\mathrm{CR}}(r, z) \rightarrow \zeta_{\mathrm{CR}}(r, z)$

Adapted from Umebayashi & Nakano (1981), Eq. 23:

$$\zeta_{\mathrm{p}}(x) = \frac{2\Omega}{\overline{\mathcal{E}}_k} \int \left(-\frac{dE}{dx} \right)_{\mathrm{p}} \frac{dn_{\mathrm{CR}}(x)}{dE} dE$$

Intensity of cosmic rays, Eq. 21:

$$\frac{dn_{\mathrm{CR}}}{dE} = 9.4 \times 10^{-1} (E_0 + E)^{-2.6} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1} \mathrm{GeV}^{-1}$$

$\overline{\mathcal{E}}_k = 36\,\mathrm{eV}$ - average energy loss per ionisation

Results: $n_{\rm CR}(r,z) \rightarrow \zeta_{\rm CR}(r,z)$

Adapted from Umebayashi & Nakano (1981), Eq. 23:

$$\zeta_{\rm p}(x) = \frac{2\Omega}{\mathcal{E}_k}\int\left(-\frac{dE}{dx}\right)_{\rm p}\frac{dn_{\rm CR}(x)}{dE}dE$$

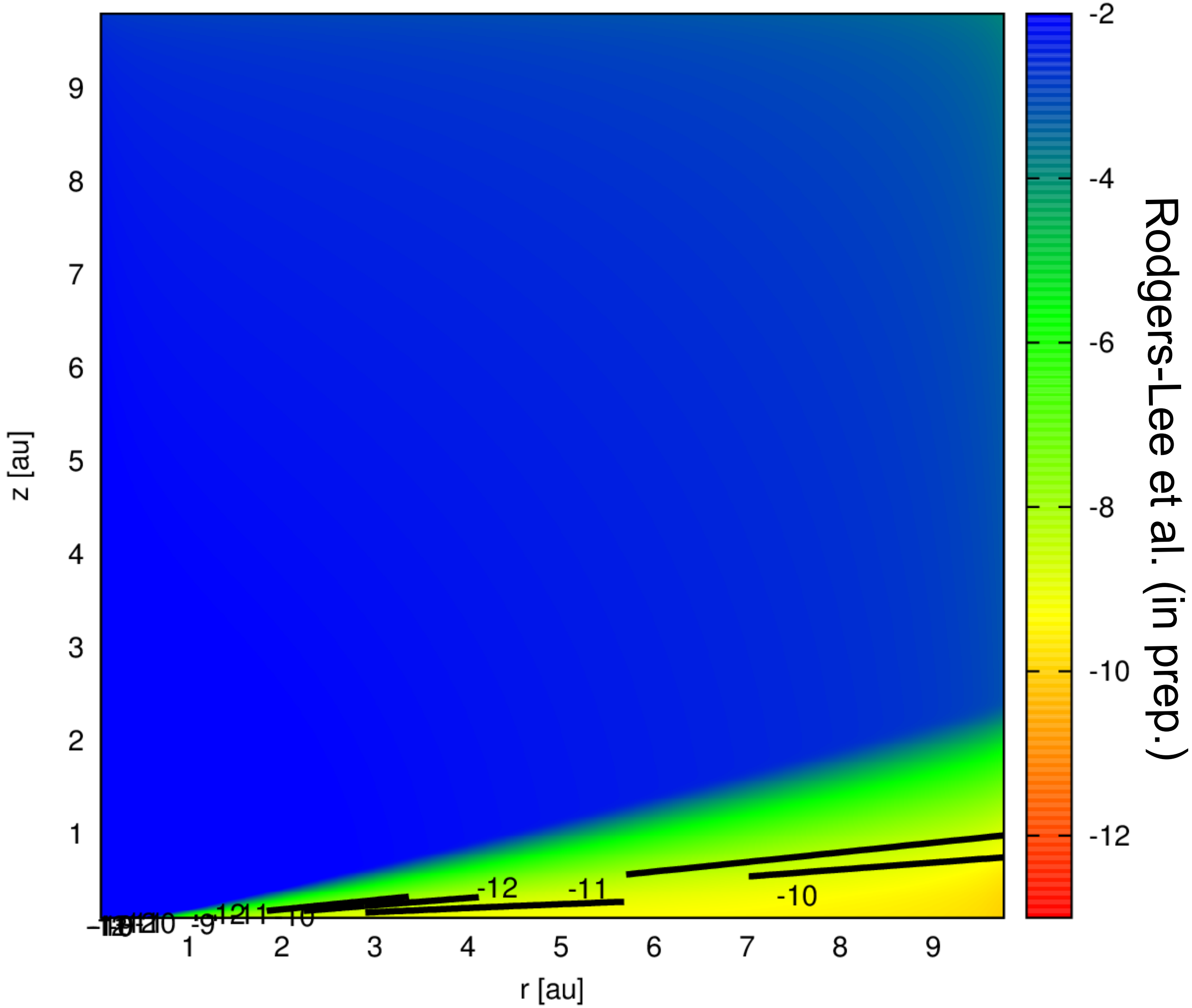
$-\frac{dE}{dx} \rightarrow\ \sim 10^{-13}\,{\rm GeV cm}^{-1}$

$\frac{dn_{\rm CR}(x)}{dE} \rightarrow n_{\rm CR}(r,z)$

$$\zeta_{\rm p}(r,z) \sim 10^{-17}{\rm s}^{-1}\left(\frac{n_{\rm CR}(r,z)}{4\times10^{-10}{\rm cm}^{-3}}\right)$$

Ionisation fraction: $x_e(r,z) = \sqrt{\frac{\zeta_{\rm CR}(r,z)}{\beta n_{\rm n}}}$

(Fromang et al., 2002)



Ionisation fraction:
Colour scale

Contours:
Plasma density

Ionisation fraction
is sufficiently high

Observational evidence

Pros:

Herschel observations (Aresu et al., 2014)

Podio et al. 2014, Ceccarelli et al. 2014

Cons:

TW Hya (Cleeves et al., 2015)

Conclusions & Future work

- Preliminary results: low energy protostellar cosmic rays are an effective source of ionisation
- Will lead to changes in the strength of non-ideal MHD effects & efficacy of the MRI/MCWs

And up next....

- Calculate $\zeta(r,z)$ for x-rays to compare qualitatively
- Investigate different density profiles
- Resolution study