Magnetically Controlled Flows in Planetary Winds and Star/Planet Interactions

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Radio Exploration of Planetary Habitability

Palm Springs, CA, May 2017

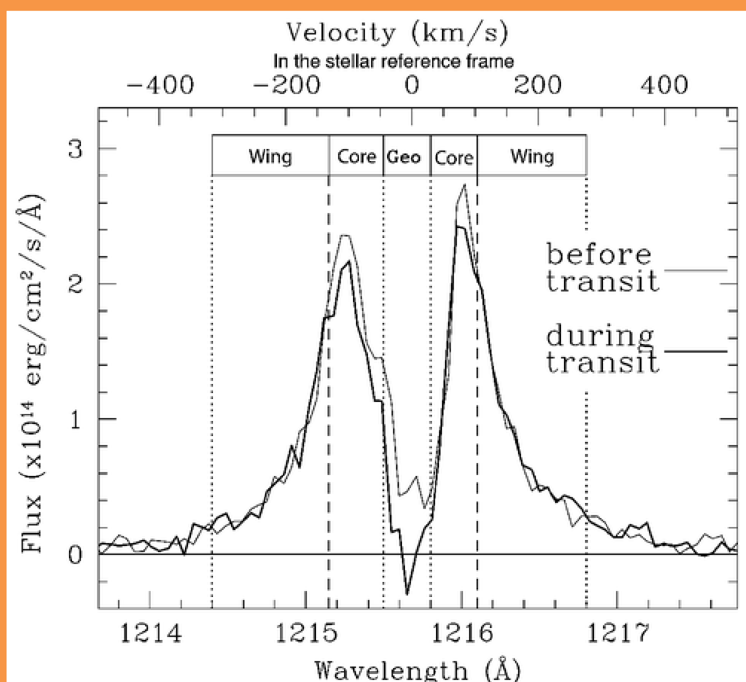
Executive Summary

- ***Outflows are observed for Hot Jupiters***
- ***Flow is Magnetically Controlled, so Magnetic Fields determine Geometry***
- ***Geometry Matters: Flow must pass through Sonic Transition***
- ***For Steady State, we have developed Analytic Methods to describe the Flow (can be used in Many other contexts)***
- ***Numerical Results are Consistent***

Adams, 2011, ApJ; Owen & Adams, 2014 + 2016, MNRAS

Hot Jupiters can Evaporate

- HD209458b (Vidal-Madjar et al. 2003, 2004; Desert et al. 2008; Sing et al. 2008; Lecavelier des Etangs et al. 2008)
- HD189733b (Lecavelier des Etangs et al. 2010)



$$\frac{dM}{dt} = 10^{10} - 10^{11}\, g/s$$

$$\left(1\,\frac{m_J}{Gyr} \approx 6 \times 10^{13}\, g/s\right)$$

Hot Jupiter Systems

$$M_* = 1 M_{SUN} \quad F_{UV} » 100 - 1000 \ (cgs)$$

$$M_P » 1 M_{JUP} \quad R_P » 1.4 R_{JUP}$$

$$B_* » 1 \ Gauss \quad B_P » 1 \ Gauss$$

$$v_{orb} » 0.05 AU \quad P_{orb} » 4 day \quad e = 0$$

$$v_{orb} » 10 R_* » 100 R_P \quad v_{orb} >> R_* >> R_P$$

Basic Regime of Operation

$$\frac{dM}{dt} = h\frac{pR_P^3 F_{UV}}{GM_P} \text{ » } 10^{10}\, g\ s^{-1} \text{ » } 10^{-4}\ M_J\ Gyr^{-1}$$

$$\frac{B^2}{8prv^2} \text{ » } 10^4 - 10^6\ \ (magnetically - controlled)$$

$$\frac{w_C}{G} = \frac{qB}{cmnsv} \text{ » } 10^4\ \ (well - coupled)$$

$$\frac{B_{^}}{B} = O\left(8prv^2 / B^2\right) < 10^{-4}\ \ (current - free)$$

Take-Away Point

$$\frac{B^2}{8\pi\rho v^2} = 10^4 - 10^6$$

Flow must follow the field lines…

Dimensionless Fields for Single Bodies

Ratio of outflow ram pressure to magnetic field pressure.

$$\Lambda_* = \left(\frac{2\dot{M}v}{B^2 V^2}\right)_* \approx 0.004\left(\frac{V}{R_*}\right)^4$$

$$\Lambda_P = \left(\frac{2\dot{M}v}{B^2 r^2}\right)_P \approx 0.0002\left(\frac{r}{R_P}\right)^4$$

Stellar parameter assumes Solar values for field, mass loss rate, radius, and outflow speed. Planet parameter assumes Jovian values for field and radius, mass loss rate = 10^{10} g/sec, and speed = 10 km/s (i.e., at sonic point; even smaller near surface!)

Parameters for Star-Planet Interactions

Ratio of the stellar pressure (from wind/field) evaluated at the planet location to the pressure from planet itself.

Magnetic field pressure from the planet dominates (near the surface).

$$\Pi_{WW} = \frac{(\dot{M}v)_* r^2}{(\dot{M}v)_P V^2} \approx 0.10 \left(\frac{r}{R_P}\right)^2$$

$$\Pi_{WB} = \frac{2\dot{M}_* v_*}{B_P^2 V^2}\left(\frac{r}{R_P}\right)^6 \approx 4 \times 10^{-5}\left(\frac{r}{R_P}\right)^6$$

$$\Pi_{BW} = \frac{B_*^2 r^2}{2\dot{M}_P v_P}\left(\frac{R_*}{V}\right)^6 \approx 0.005\left(\frac{r}{R_P}\right)^2$$

$$\Pi_{BB} = \left(\frac{B_*}{B_P}\right)^2\left(\frac{r}{R_P}\right)^6\left(\frac{R_*}{V}\right)^6 \approx 10^{-6}\left(\frac{r}{R_P}\right)^6$$

TWO COUPLED PROBLEMS

- LAUNCH of the outflow from planet
- PROPAGATION of the outflow in the joint environment of star and planet, including gravity, stellar wind, stellar magnetic field
- Matched asymptotics: Outer limit of the inner problem (launch of wind) provides the inner boundary condition for the outer problem (propagation of wind)

This Work Focuses on Launch of the Wind

The Coordinate System

$$\vec{B} = B_P\left[\xi^{-3}\left(3\cos\theta\ \hat{r} - \hat{z}\right)\right] + B_*(R_*/\varpi)^3\hat{z}$$

$$p = \left(\beta\xi - \xi^{-2}\right)\cos\theta \qquad q = \left(\beta\xi^2 + 2/\xi\right)^{1/2}\sin\theta$$

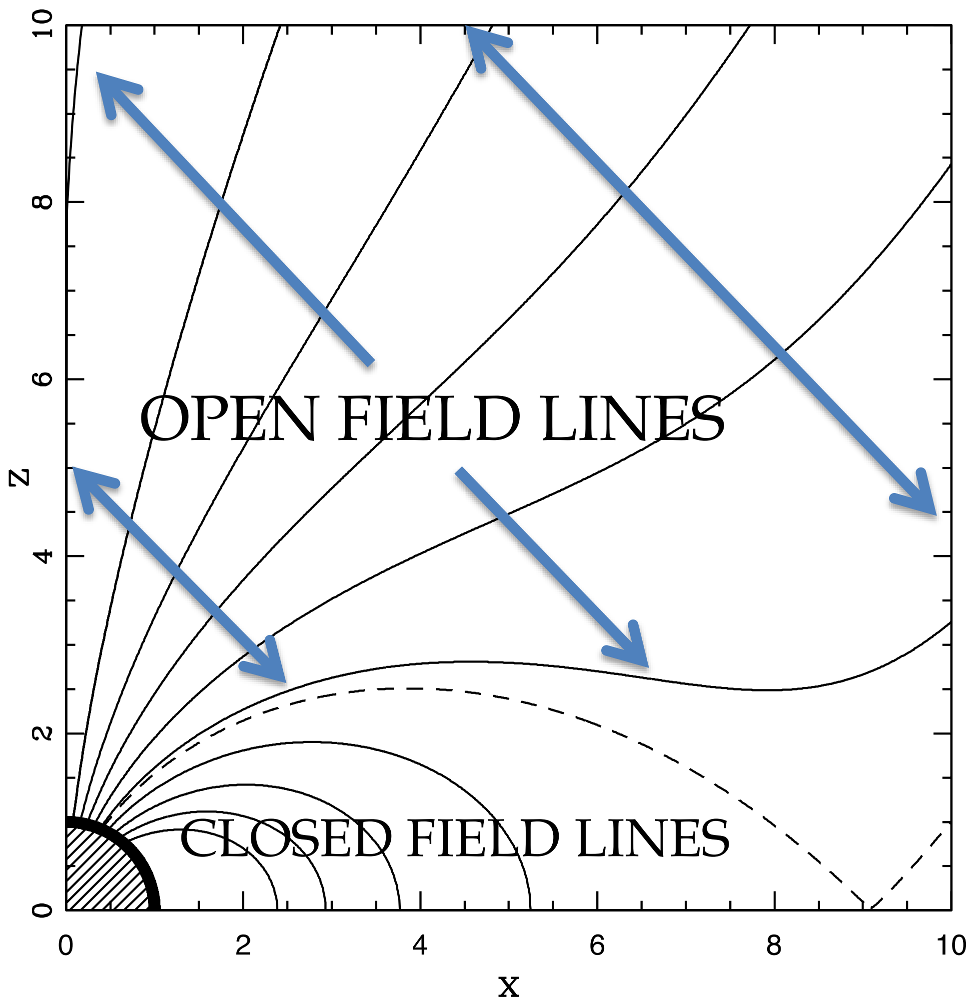
$$where \quad \beta = (B_* R_*^3/\varpi^3)/B_P \approx 10^{-3} \quad and \quad \xi = r/R_*$$

$$\nabla p = f(\xi)\cos\theta\ \hat{r} - g(\xi)\sin\theta\ \hat{\theta}$$

$$\nabla q = \left[g(\xi)\sin\theta\ \hat{r} + f(\xi)\cos\theta\ \hat{\theta}\right] g^{-1/2}(\xi)$$

$$where \quad f = \beta + 2\xi^{-3} \quad and \quad g = \beta - \xi^{-3}$$

Magnetic Field Configuration



Magnetic field lines are lines of constant coordinate q.
The coordinate p measures distance along field lines.
Field lines are open near planetary pole and are closed near the equator. Fraction of open field lines:

$$f = 1 - \left[1 - \frac{3b^{1/3}}{2+b}\right]^{1/2}$$

Equations of Motion

Steady-state flow along field-line direction:
Fluid fields are functions of coordinate p only.

$$\alpha \frac{\partial u}{\partial p} + u \frac{\partial \alpha}{\partial p} = -\frac{\alpha u}{h_q h_\phi} \frac{\partial}{\partial p}\left(h_q h_\phi\right)$$

$$u \frac{\partial u}{\partial p} + \frac{1}{\alpha} \frac{\partial \alpha}{\partial p} = -\frac{\partial \psi}{\partial p} = -\frac{\partial \psi}{\partial \xi} \frac{\partial \xi}{\partial p}$$

$$u = \frac{v}{a_S} \qquad \alpha = \frac{\rho}{\rho_1} \qquad \psi = \frac{\Psi}{a_S^2} \rightarrow \frac{b}{\xi} \qquad b \equiv \frac{GM_P}{R_P a_S^2}$$

Two parameters specify the dimensionless problem

$$b \,{}^{\circ}\, \frac{GM_P}{R_P a_S^2} \text{»} 10$$

$$b \,{}^{\circ}\, \frac{B_*\left(R_* / v\right)^3}{B_P} \text{»} 0.001$$

Solutions

$$\frac{b}{3} = \frac{2f^2 - \left(g^2/f + 2g + 2f\right)q^2/x^2}{f^3x^2 + \left(g^2 - f^2\right)q^2}$$

Sonic point

$$l = qH_s^{-1/2}\exp\left[\frac{l^2H_1}{2q^2} + \frac{b}{x_s} - b - \frac{1}{2}\right]$$

Continuity eq. constant

$$f = b + 2x^{-2}, \quad g = b - x^{-3}, \quad and$$

$$H = f^2\cos^2 q + g^2\sin^2 q, \quad \sin^2 q = q^2/(bx^2 + 2/x)$$

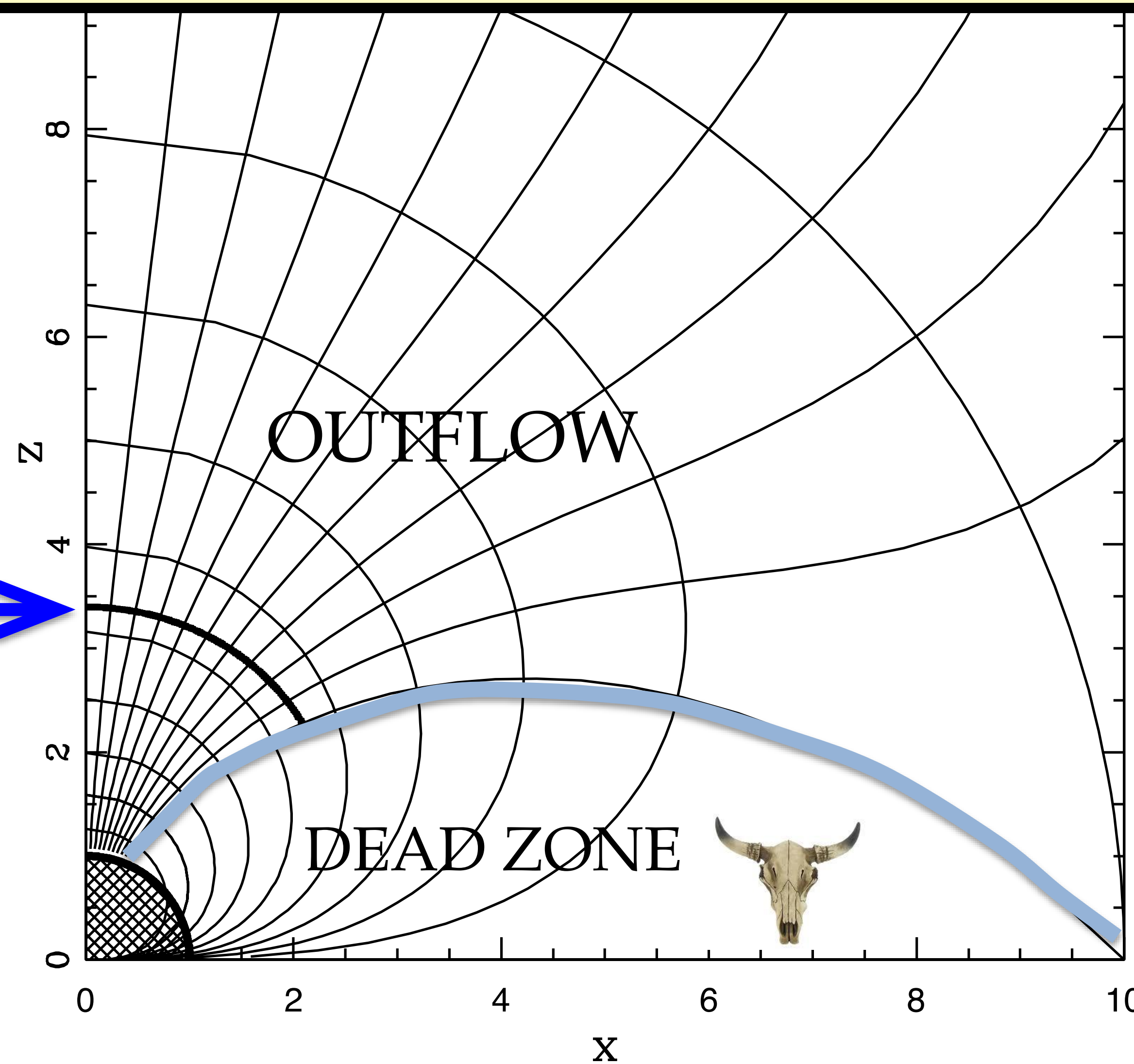
Sonic Surface

Sonic Surface

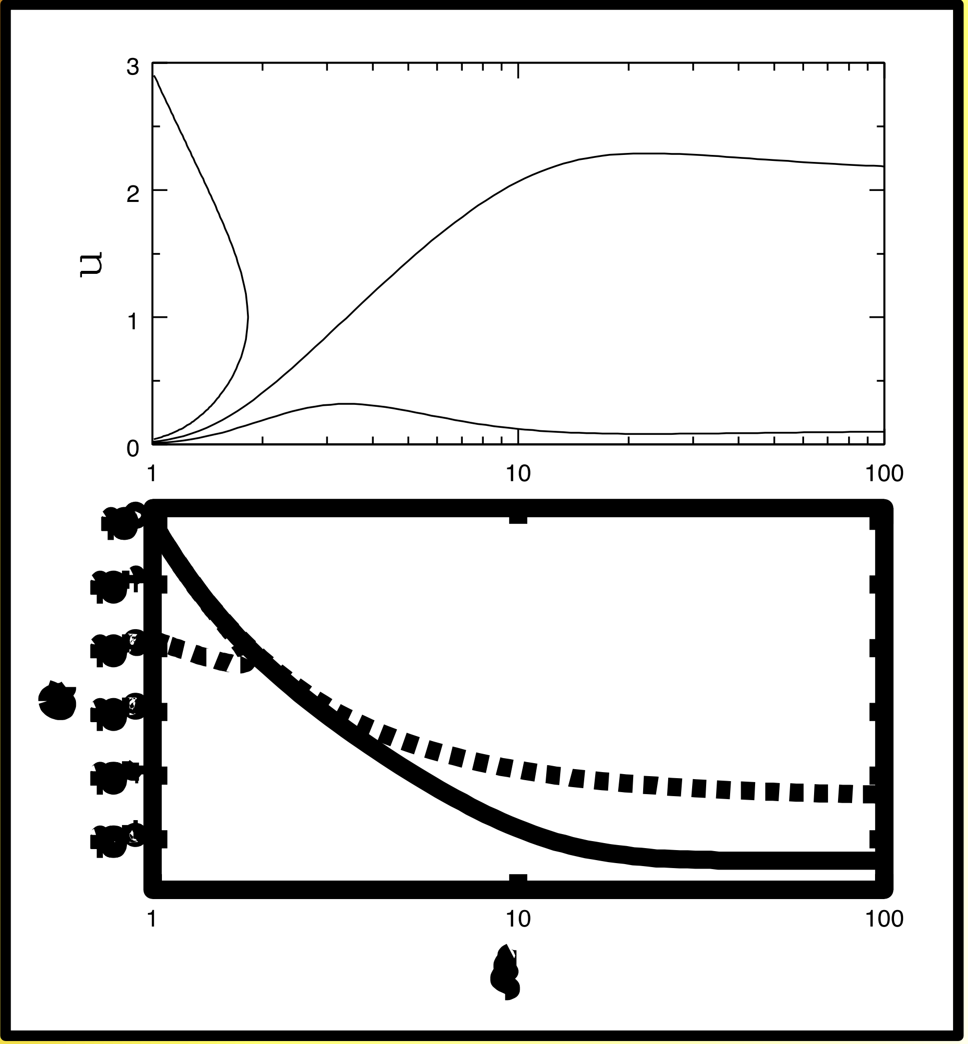
at x » 3.3,

different for

each streamline



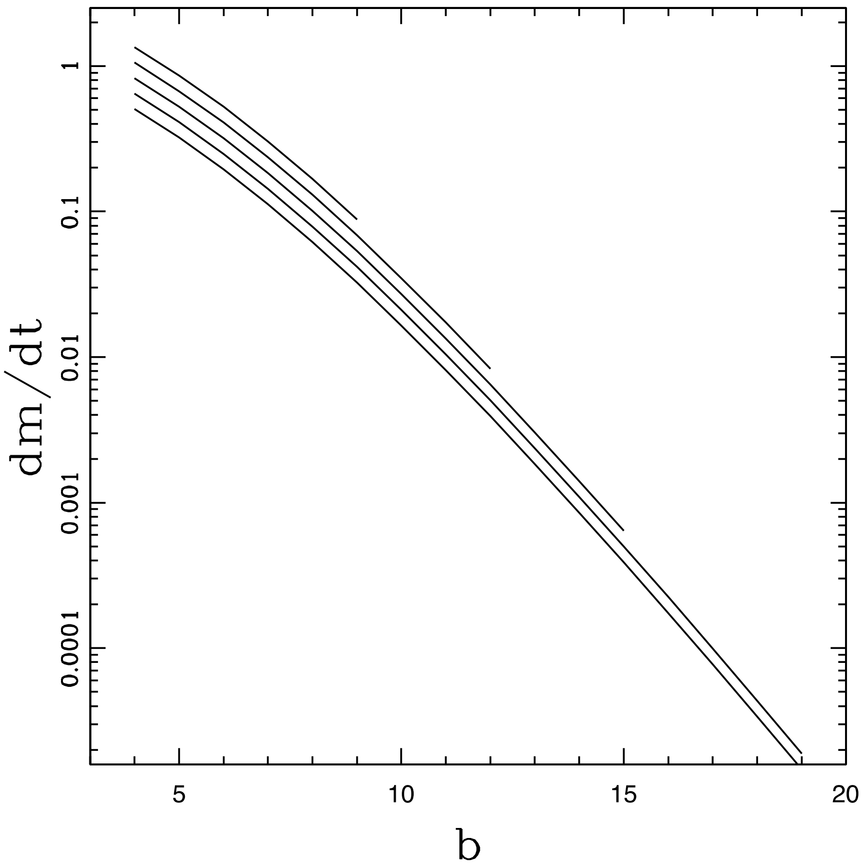
Fluid Field Solutions

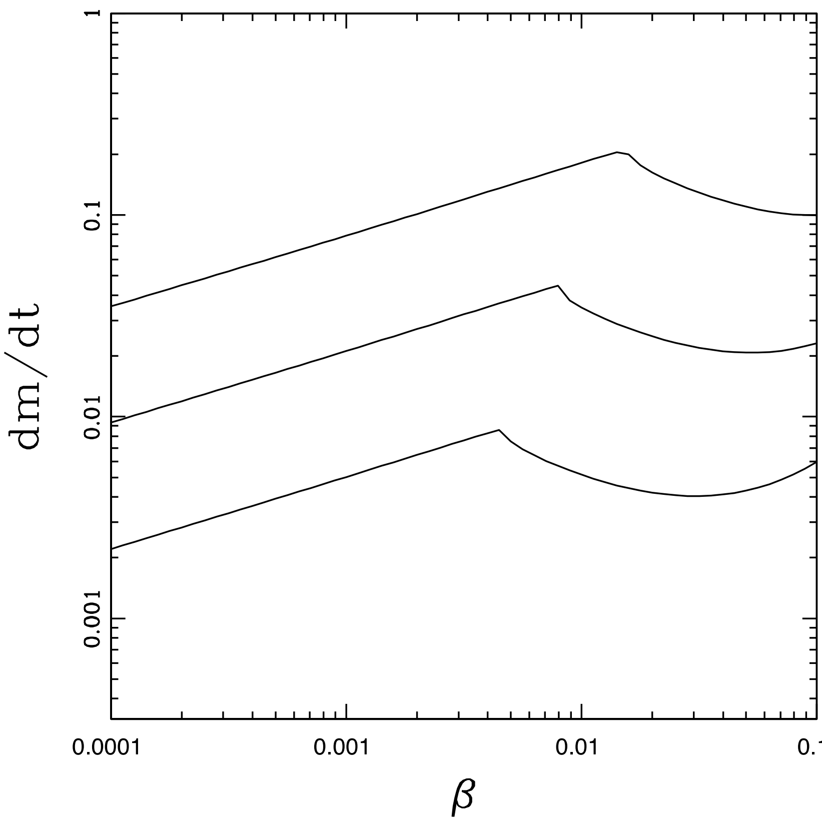


Mass Outflow Rates

$$\frac{dm}{dt} = 4p \int_0^{q_X} / \; dq$$

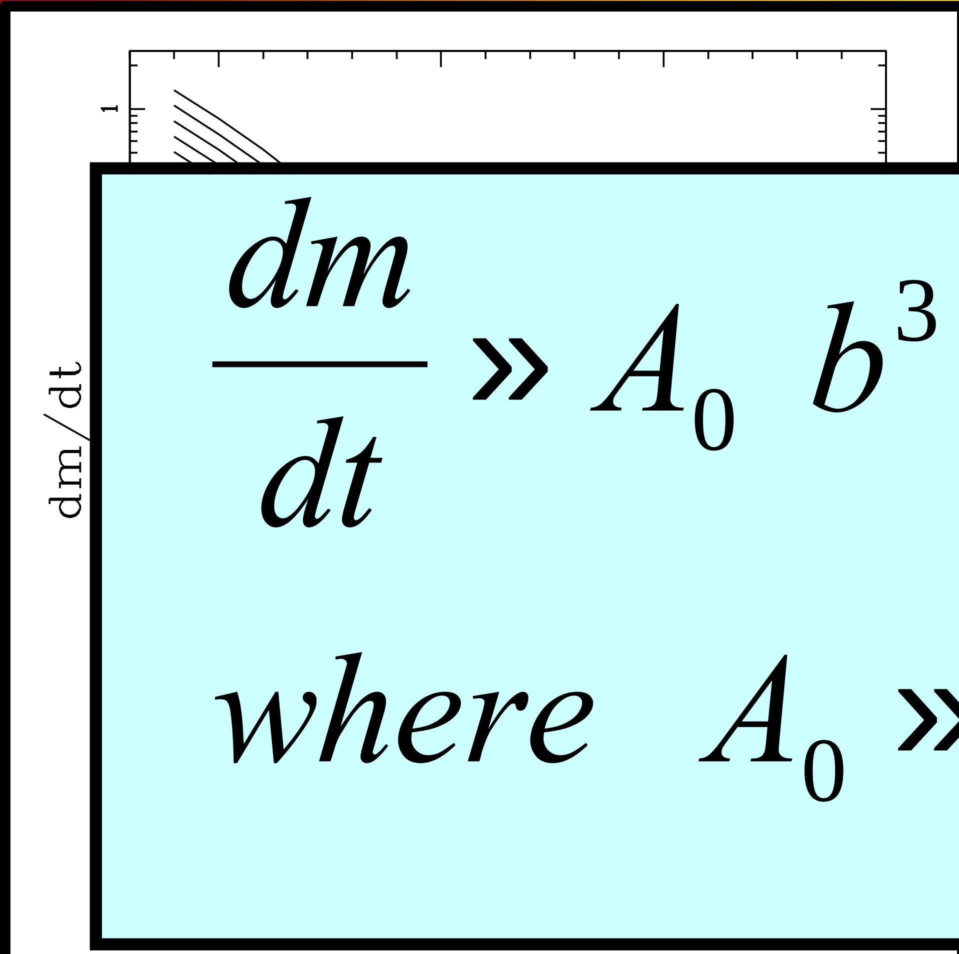
$$b = (B_* R_*^3 / v^3) / B_P$$





$$b = GM_P / a_S^2 R_P$$

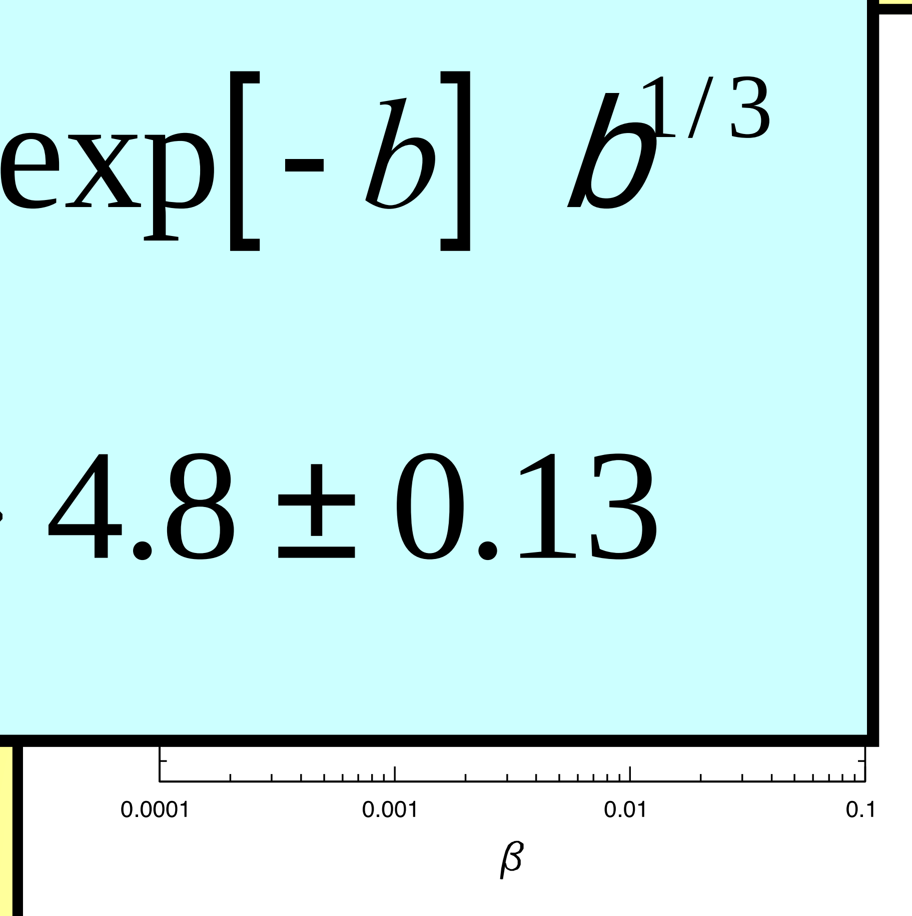
Mass Outflow Rates



$$b = (B_* R_*^3 / v^3) / B_P$$

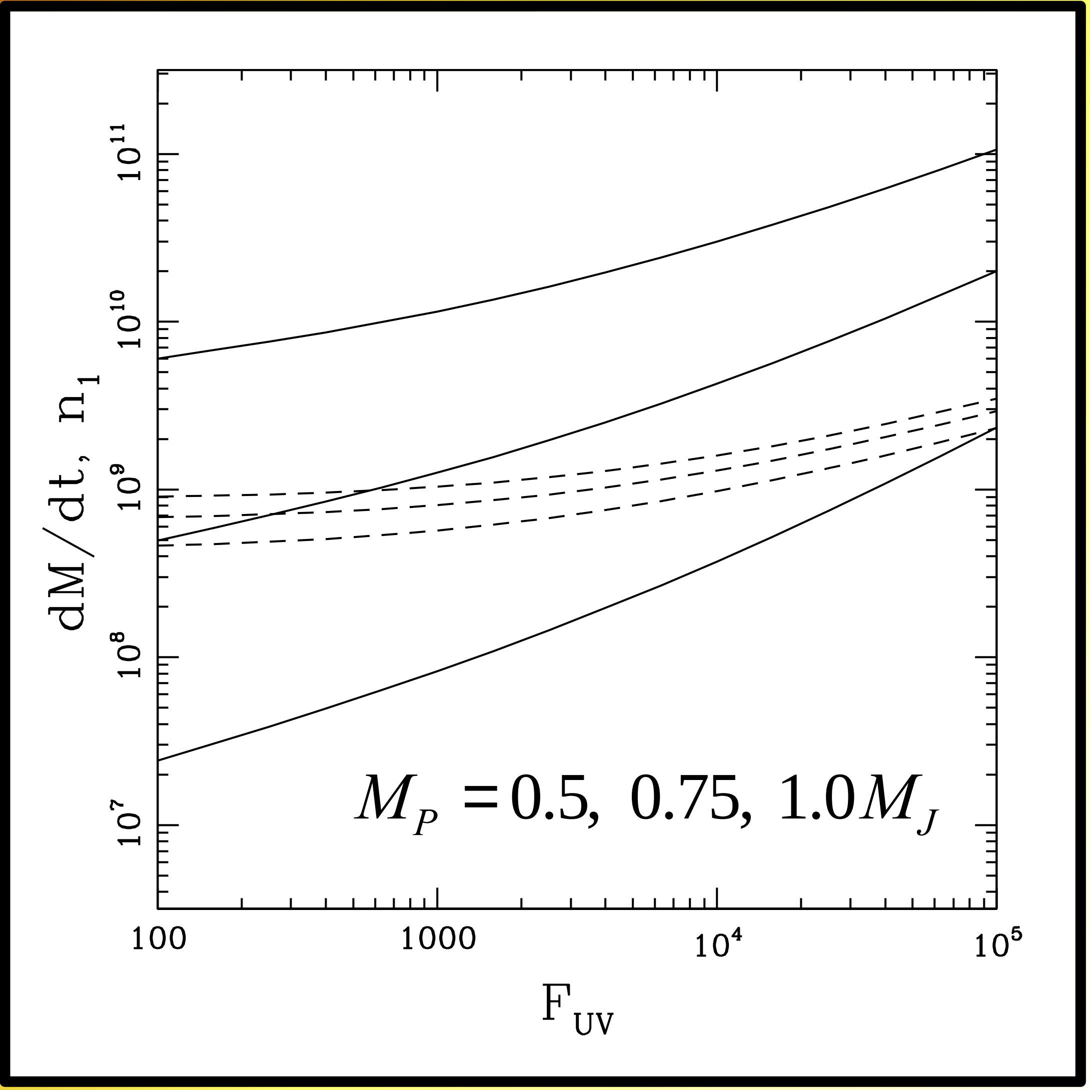
$$\frac{dm}{dt} \approx A_0 \; b^3 \exp[-b] \;\; b^{1/3}$$

$$where \quad A_0 \approx 4.8 \pm 0.13$$



$$b = GM_P / a_S^2 R_P$$

Physical Outflow Rate vs Flux

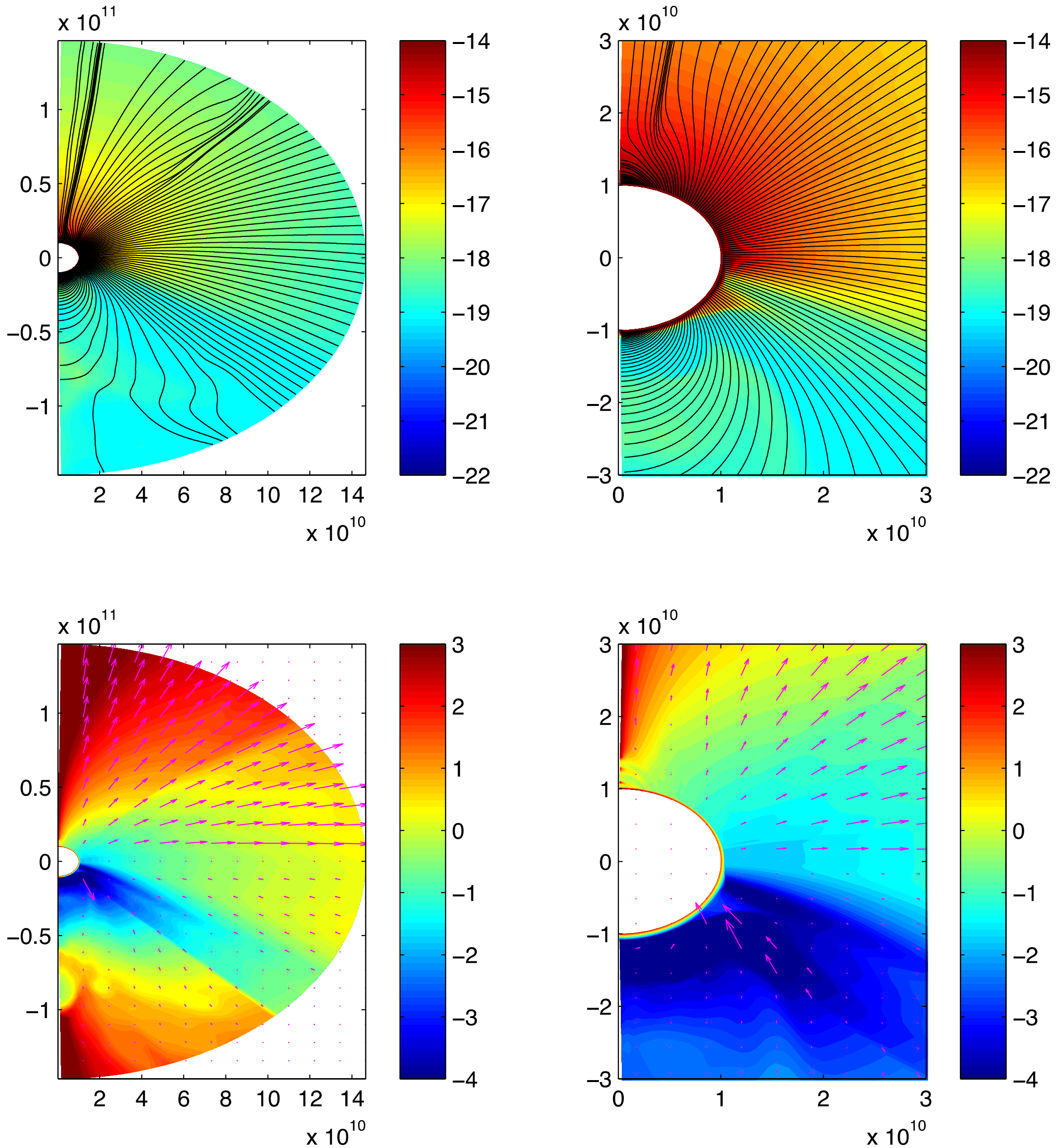


Numerical Simulations

- ***MHD simulations -- from James Owen***
- ***Use relatively weak fields and strong UV fluxes – still magnetically controlled***
- ***Start with all longitudes – then focus on day side of planet (no night side flow)***
- ***Background stellar field in z-direction***
- ***Basic consistency with analytic work***

$$b = \frac{B_*}{B_P}\left(\frac{R_*}{a}\right)^3 = 0,\ \ 0.003,\ \ 0.03 \qquad F_{UV} = 10^5 - 10^6\, erg\ cm^{-2}\, s^{-1}$$

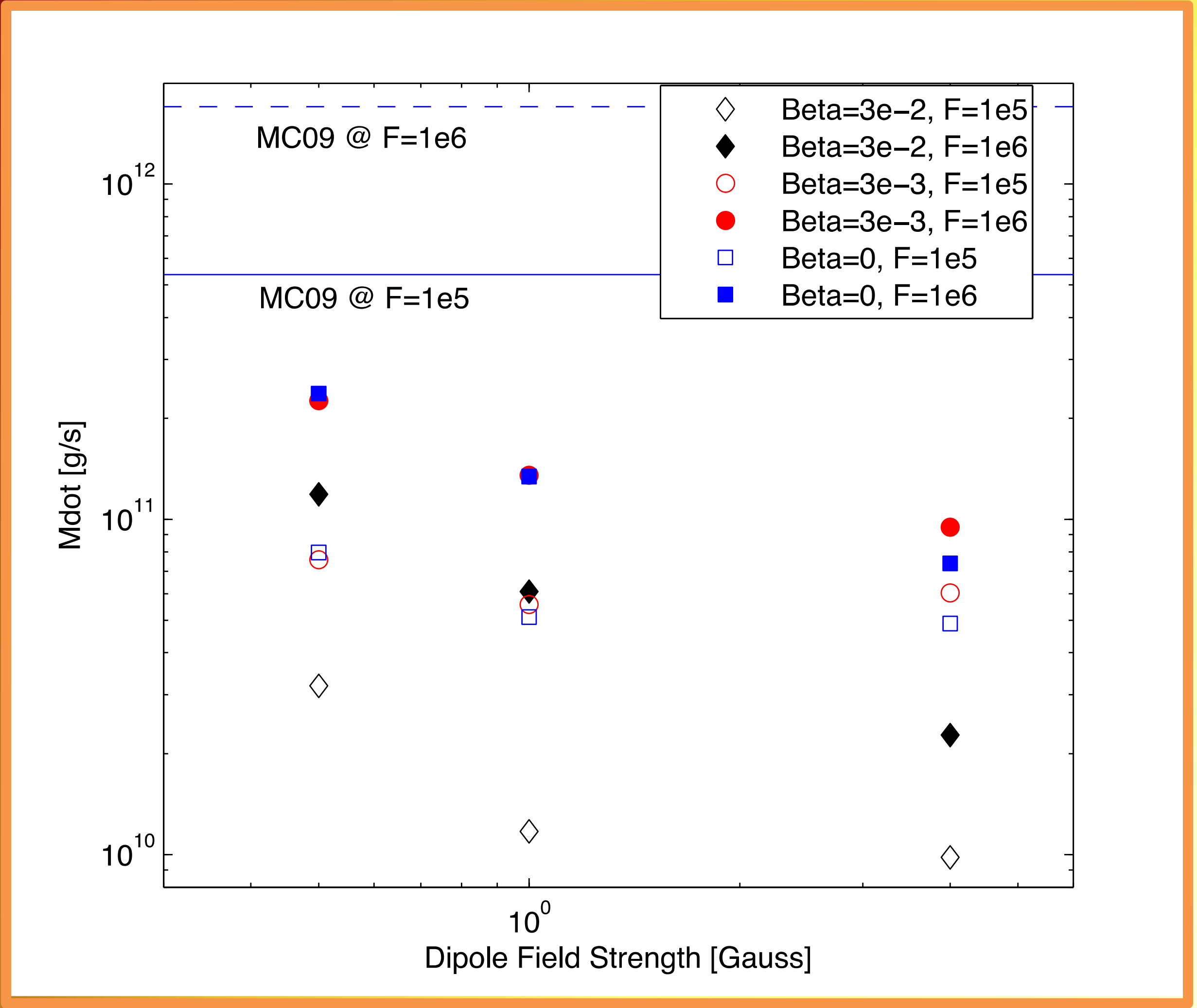
Numerical Simulations



Including the Magnetic Field acts to suppress mass outflow from night side of the planet.

James Owen & F. Adams 2014 MNRAS

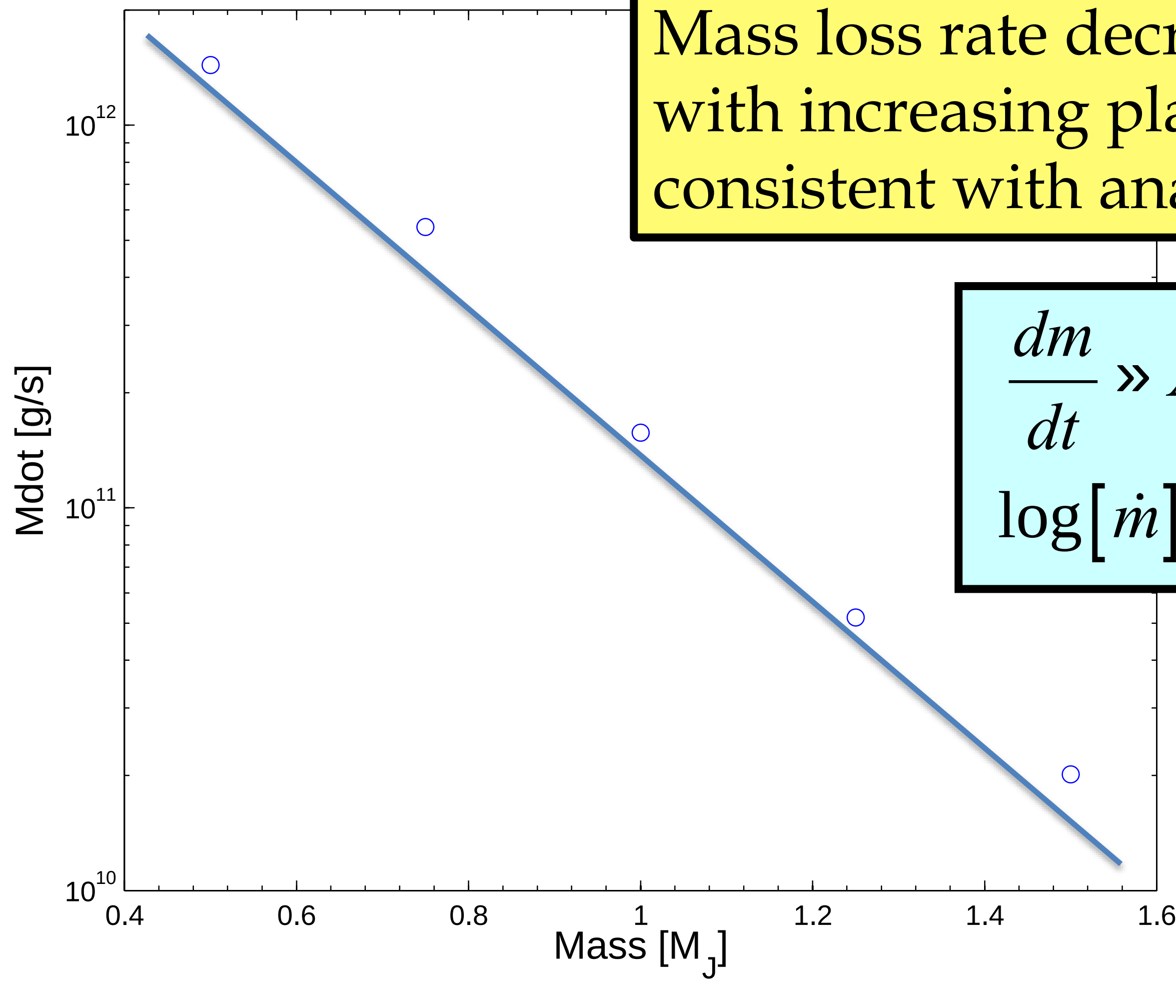
Mass Loss Rate vs Field Strength



Including the Magnetic Field acts to suppress mass loss rates (compared to field-free case).

James Owen & F. Adams 2014 MNRAS

Mass Loss Rate vs Planet Mass



Mass loss rate decreases exponentially with increasing planetary mass -- consistent with analytic expectations.

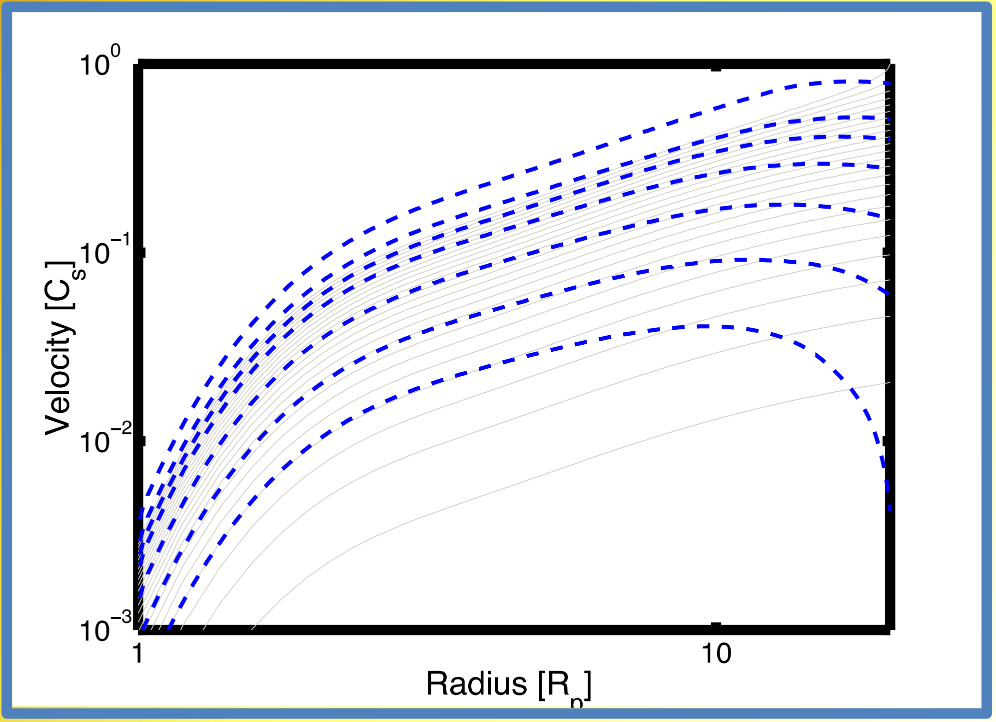
$$\frac{dm}{dt} \approx A_0 \quad b^3 \exp[-b] \quad b^{1/3}$$

$$\log[\dot{m}] = const + 3\log[b] - b$$

James Owen & F. Adams 2014 MNRAS

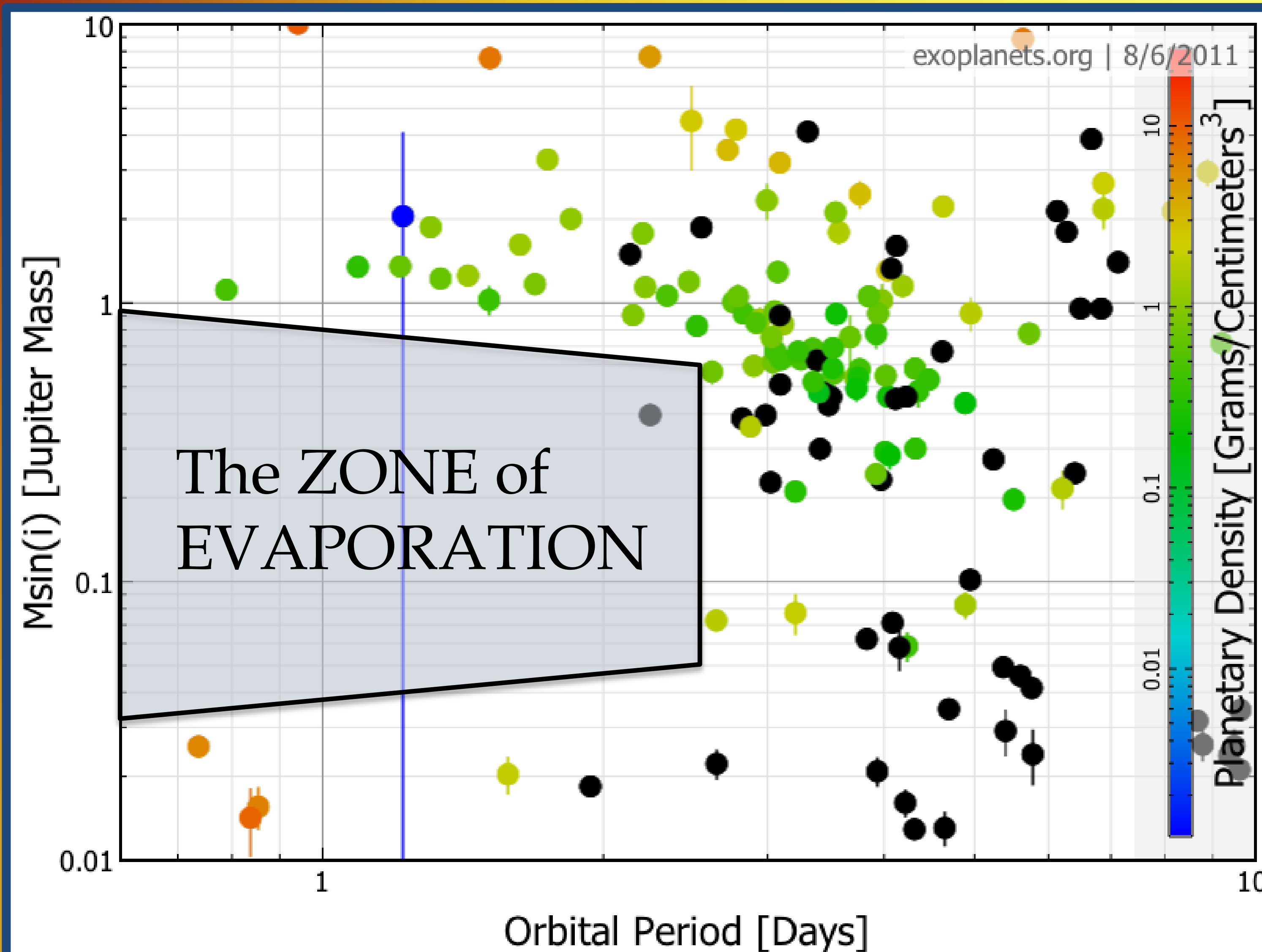
Breeze Solutions

For field lines that do not allow sonic transitions, the flow must be time dependent – get breeze solutions.



(Owen & Adams 2016, MNRAS, 456, 3053)

Implication/Prediction



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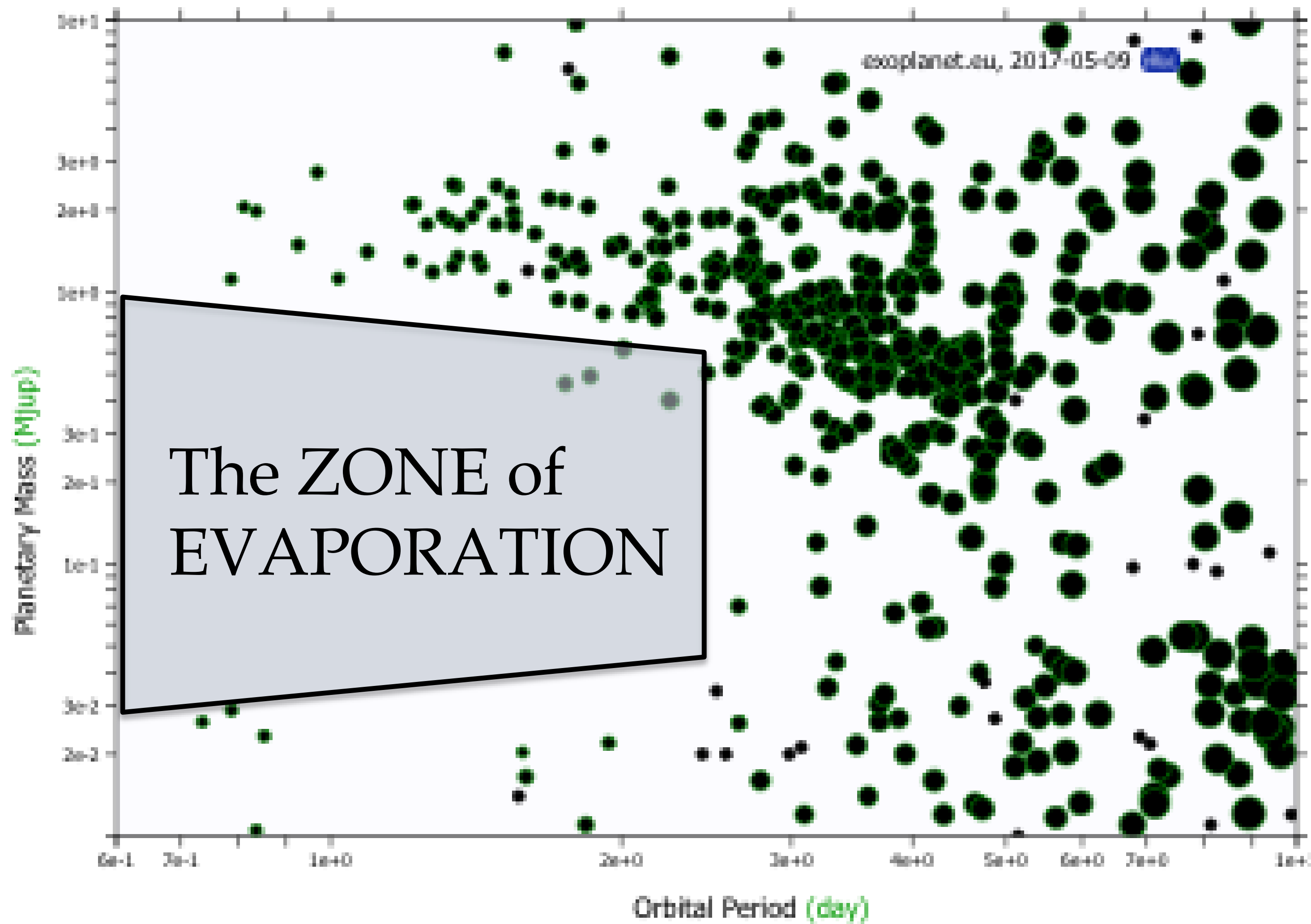
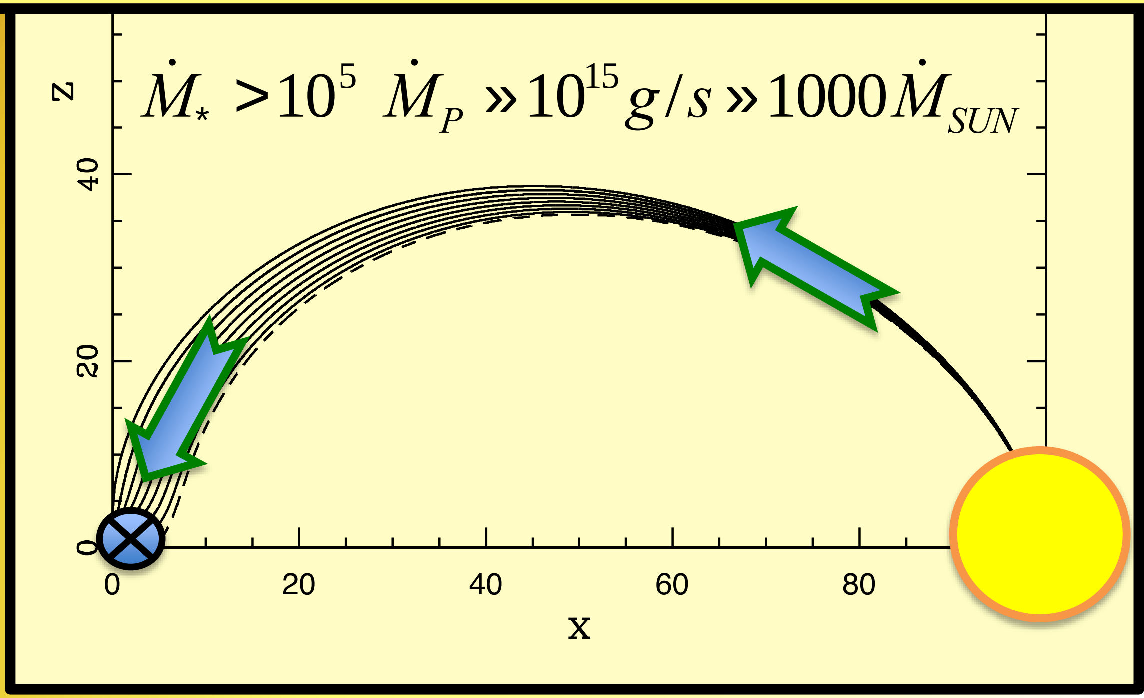


The Extreme Regime

In systems where the stellar outflow and the stellar magnetic field are both sufficiently strong, the Planet can Gain Mass from the Star



Conclusion

- Planetary outflows magnetically controlled
- Outflow rates are significantly *lower*
- Outflow geometry markedly different:

  Open field lines from polar regions

  Closed field lines from equatorial regions

  Outflow suppressed on night side of planet

  Some field lines do not allow sonic transition
- Get time dependent breeze solutions
- Strong stellar wind - planet could gain mass
- Outflow rates sensitive to planetary mass:

$$\dot{m} \;\; \mu \;\; b^3 \exp[-b] \;\;\; b^{1/3}, \qquad b = GM_P/(a_S^2 R_P)$$

(Adams, 2011, ApJ; Owen & Adams 2014, MNRAS + 2016 MNRAS)

Every Sea has its Dragons

- Planetary and stellar magnetic field geometry can vary in complicated ways
- Interaction with stellar wind affects larger scale propagation (outer problem)
- Mass loss rates generally low so that planet mass not greatly affected
- Planetary outflows useful as diagnostic tool, but require more detailed models

Part 2 – V773 Tau

Massi et al. 2008, A&A, 480, 489

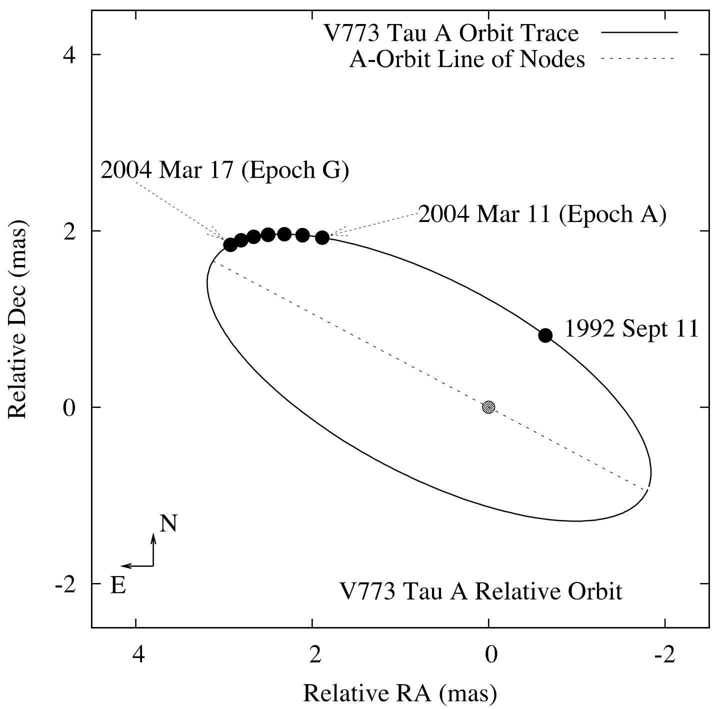


Fig. 1. Orbit of the young stellar binary system V773 Tau based on the interferometric-spectroscopic model by Boden and collaborators (2007). The secondary is given at our seven (A-G) VLBI observations (epoch 2004) and at Phillips and collaborators (1996) VLBI observation (epoch 1992). Stellar diameters are rendered to scale.

Parameters :

$M_1 = 1.54 \pm 0.14 M_{sun}$

$M_2 = 1.22 \pm 0.10 M_{sun}$

$R_1 = 2.22 \pm 0.20 R_{sun}$

$R_2 = 1.74 \pm 0.19 R_{sun}$

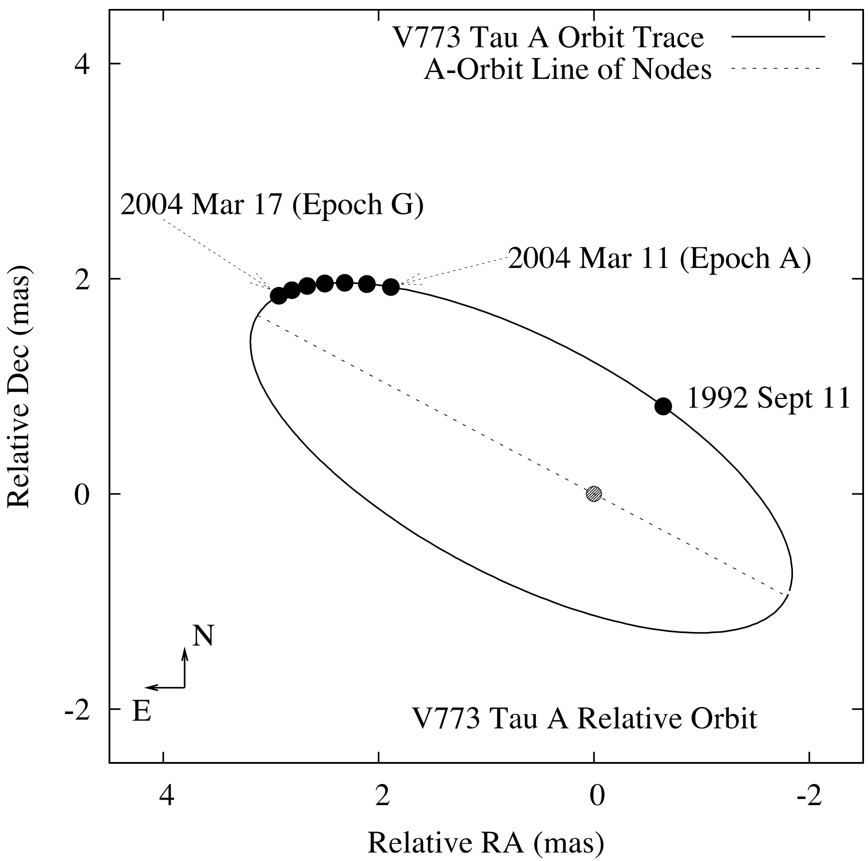
$P_{orb} = 51.1 \pm 0.2 \ day$

a_0 » $0.38 AU$

e » 0.26

$2L$ » $30 - 50 R_*$

Massi et al. 2008, A&A, 480, 489



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Radio Emission :

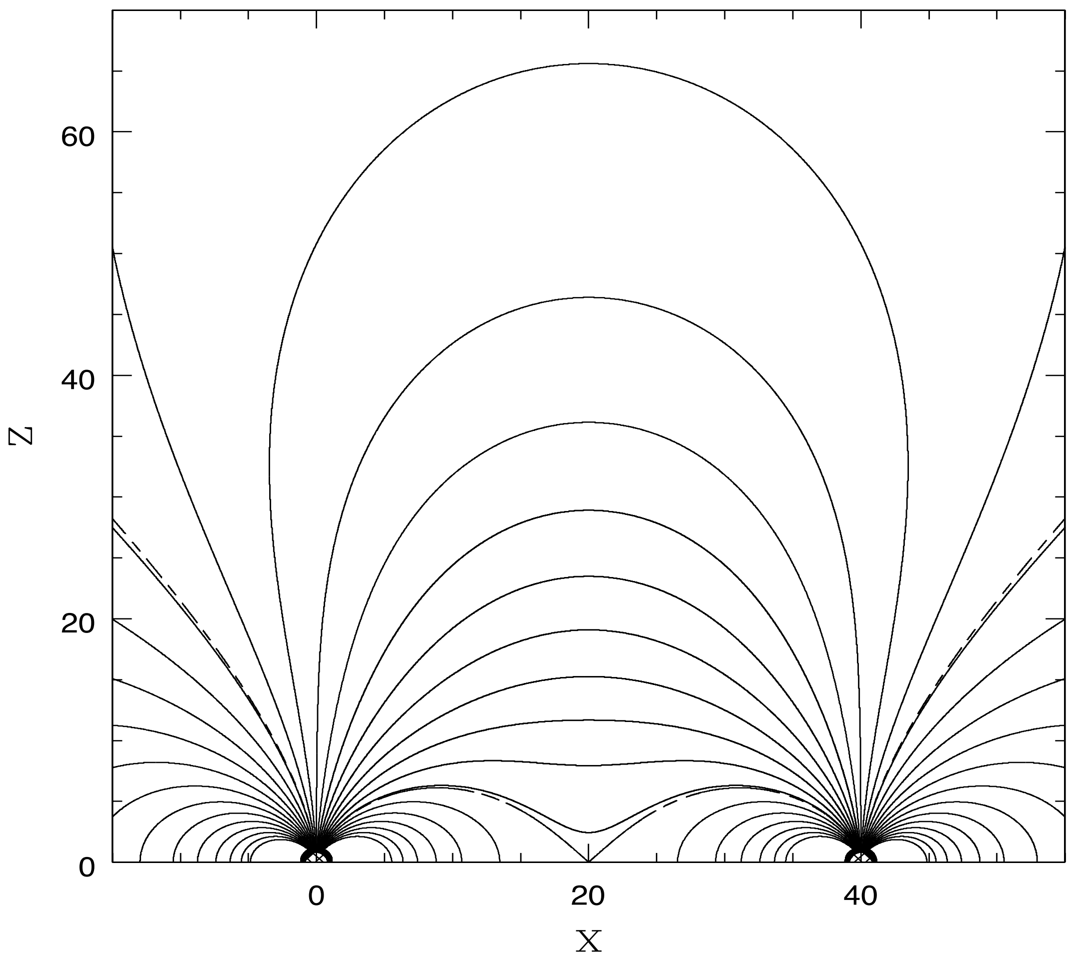
apoastron Þ

few mJy

periastron Þ

few 100*mJy*

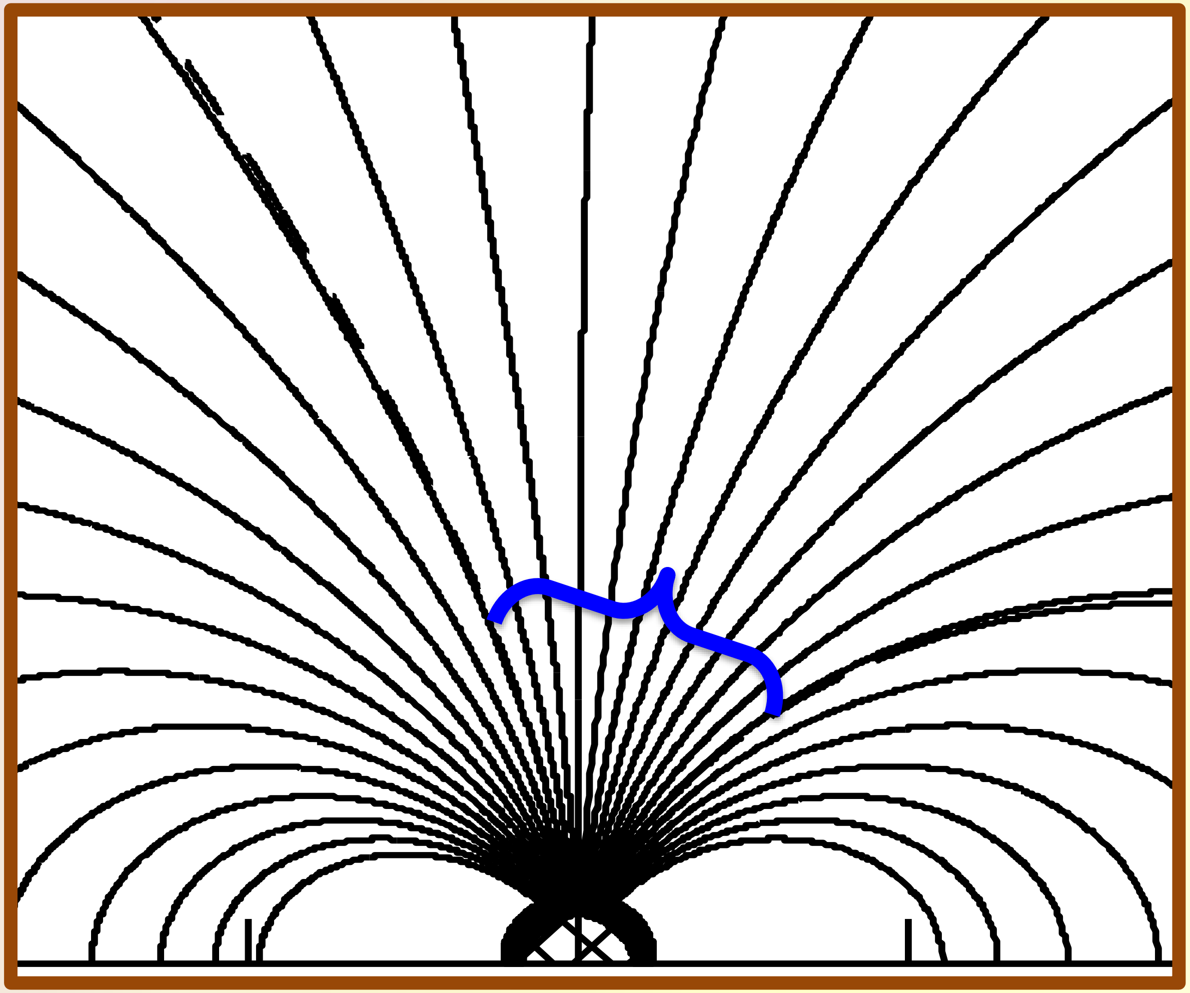
Basic Field Configuration



Magnetic Fields are assumed to be Two Anti-aligned Dipoles with surface strength of Kilogauss…

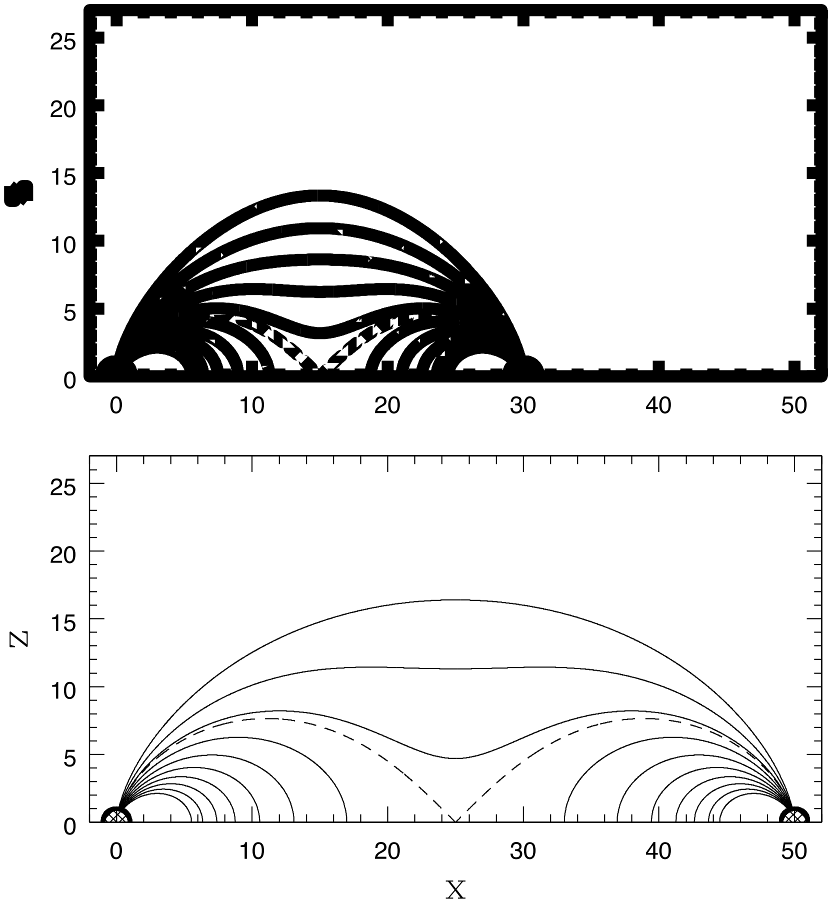
$$\begin{cases} L = 20R_* \\ 2L = 40R_* \end{cases}$$

The Polar Cap



Polar cap region contains the field lines that connect to the other star. Size and shape of the polar cap vary as the distance between the stars changes over the course of the orbit.

Magnetic field lines connect as stars come together



magnetic energy :

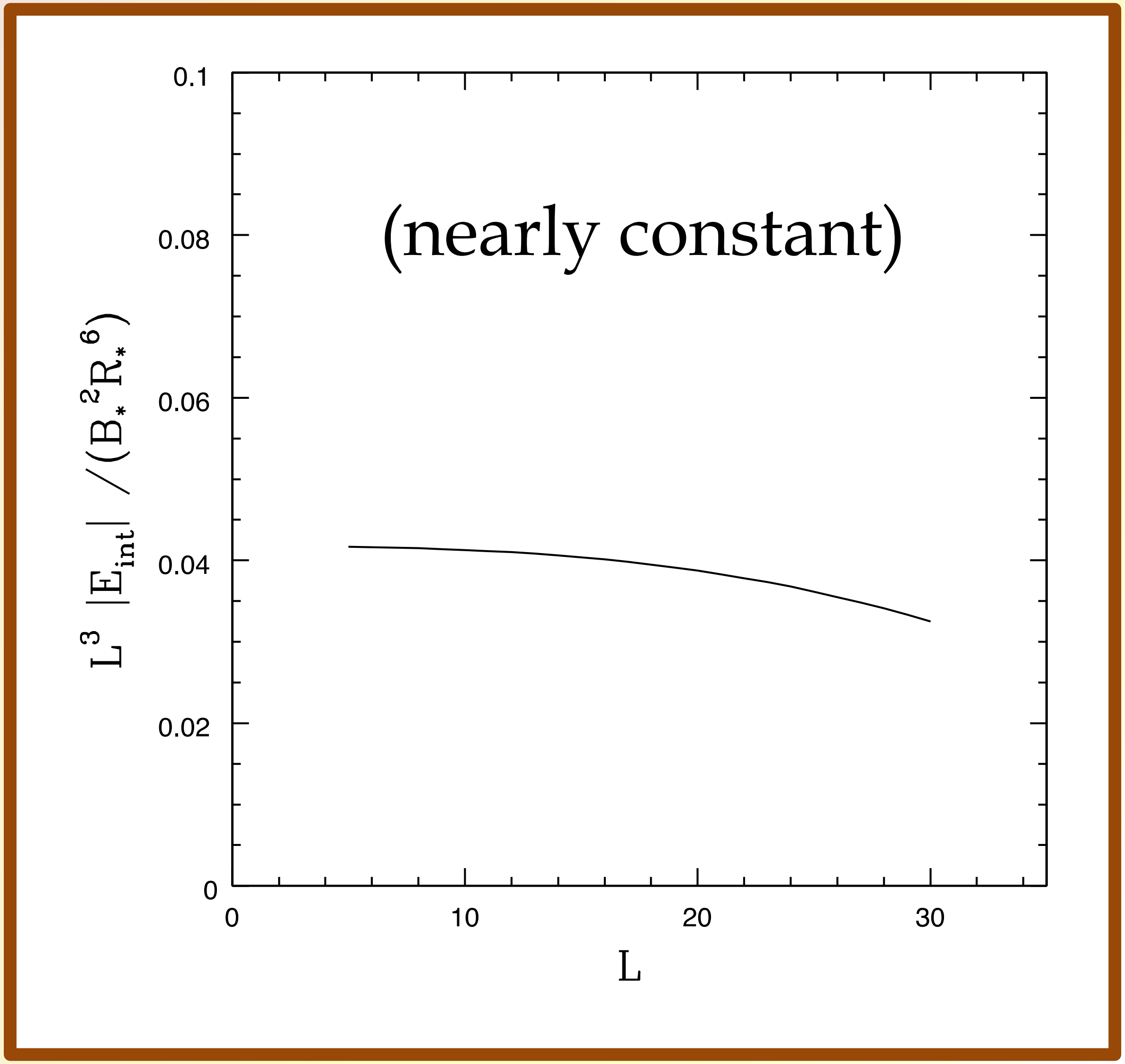
$$E_{self} \approx \frac{2}{3} B_*^2 R_*^3$$

$$E_{\rm int} \approx f\left(\frac{B_*^2 R_*^6}{24 L^3}\right) \approx 10^{35} erg$$

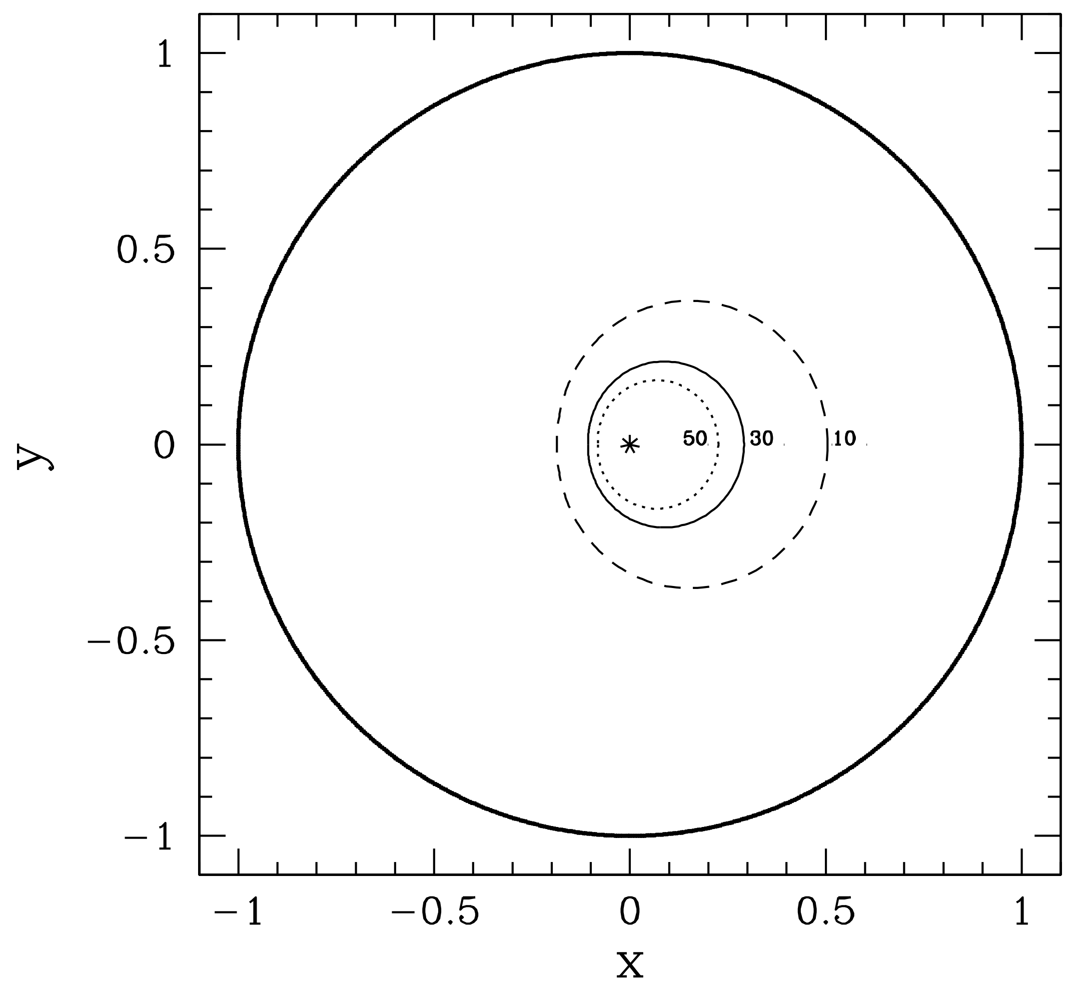
$$\therefore \quad \Delta E_{\rm int} \approx 6 \times 10^{34} erg$$

Magnetic energy released between apo- and periastron more than enough to power the observed radio emission

f-parameter vs separation

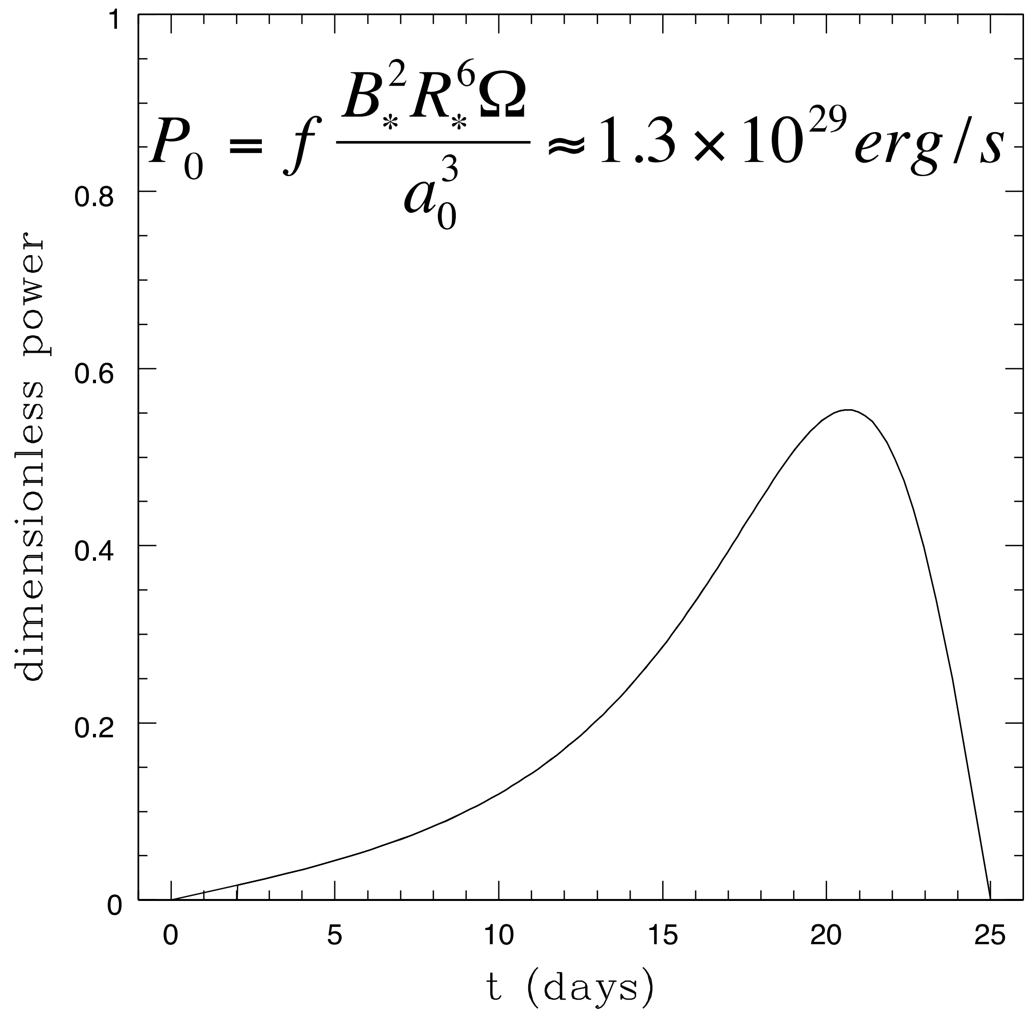


Polar Cap Size vs Separation



Available Power vs Time

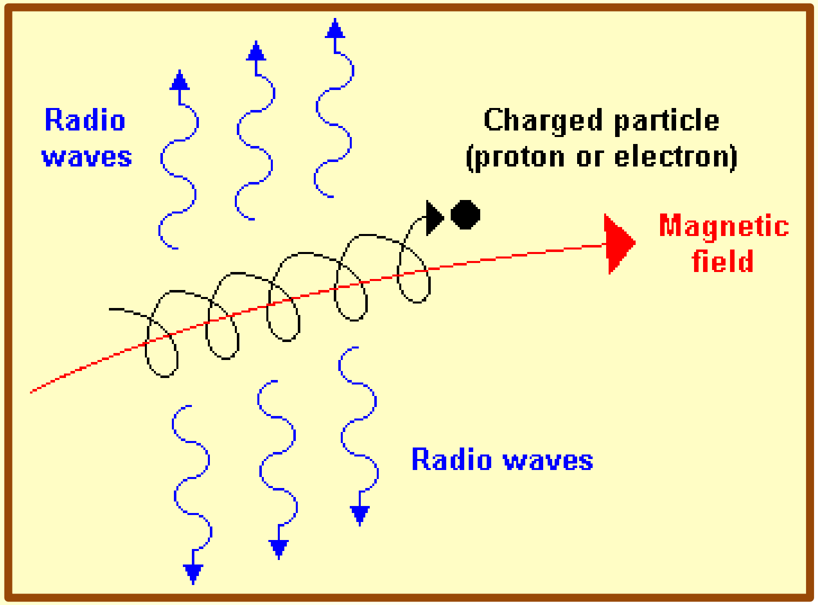
$\frac{P(t)}{P_0}$



Plenty of Power to Explain Observed Radio Emission…

Basic Physical Mechanism

[*] Energy supplied by magnetic reconnection
[*] Magnetic fields are replenished by stellar dynamo
[*] Synchrotron radiation from acceleration of electrons
[*] Electrons are accelerated by Electric Fields
[*] Electric fields produced by time-variations in the magnetic fields
[*] Require a component of the electric field along direction of magnetic field



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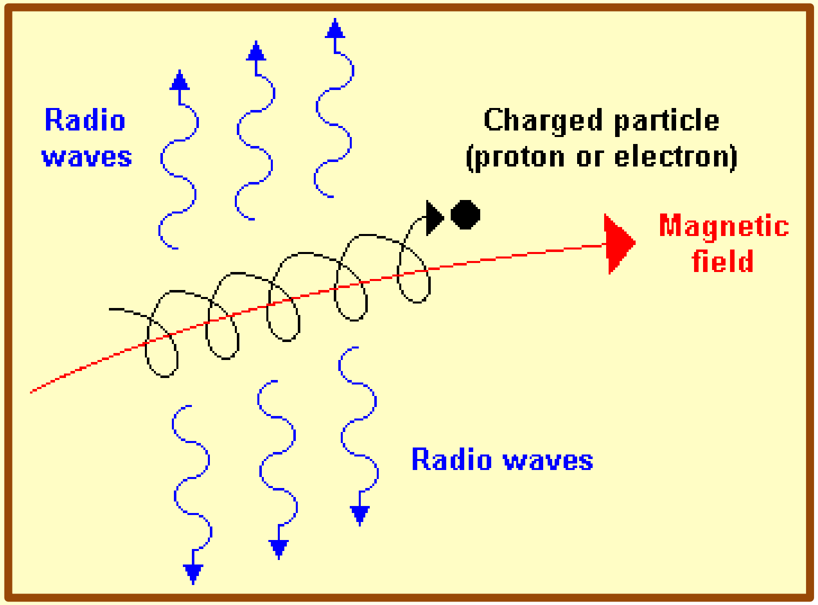
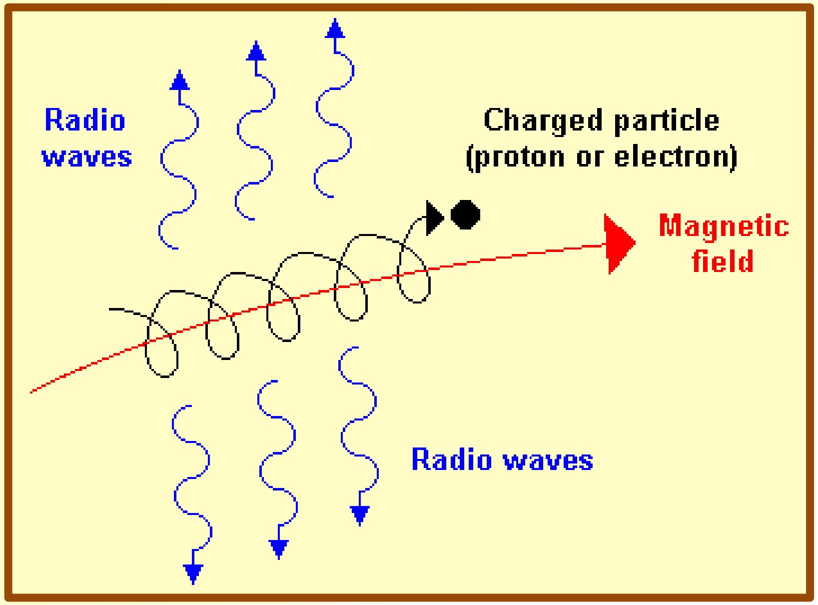


Results

[*] Power observed = 2.5e30 erg/sec
[*] Need efficient energy conversation (40%)
[*] Cutoff frequency not too much higher than 90GHz
[*] Cannot open up the field lines w. electron pressure
[*] Reconnection time =>
   n=4e6 cm^{-3}
[*] Power requirement =>
   n > 2e5 cm^{-3}



Equations for Electric Motion

The relativistic equation of motion for the electron is

$$\frac{dp}{dt} = -e\left(E + \frac{v}{c} \times B\right) + F_{rad},$$

where

$$F_{rad} = \frac{\gamma\sigma_T}{4\pi m_e c} B \times (B \times p)$$

The Thomson cross section is given by

$$\sigma_T = \frac{8\pi}{3} r_e^2, \qquad r_e = \frac{e^2}{m_e c^2}.$$

Define the frequencies

$$\omega_E \equiv \frac{eE}{m_e c}, \qquad \omega_L \equiv \frac{eB}{m_e c},$$

and expand the vector triple product to obtain the force equation

$$\frac{dp}{dt} = -\left(m_e c \vec{\omega}_E + \frac{p}{\gamma} \times \vec{\omega}_L\right) + \frac{2}{3}\frac{r_e}{c} \vec{\omega}_L (\vec{\omega}_L \cdot p) - p\omega_L^2.$$

Summary 2.0

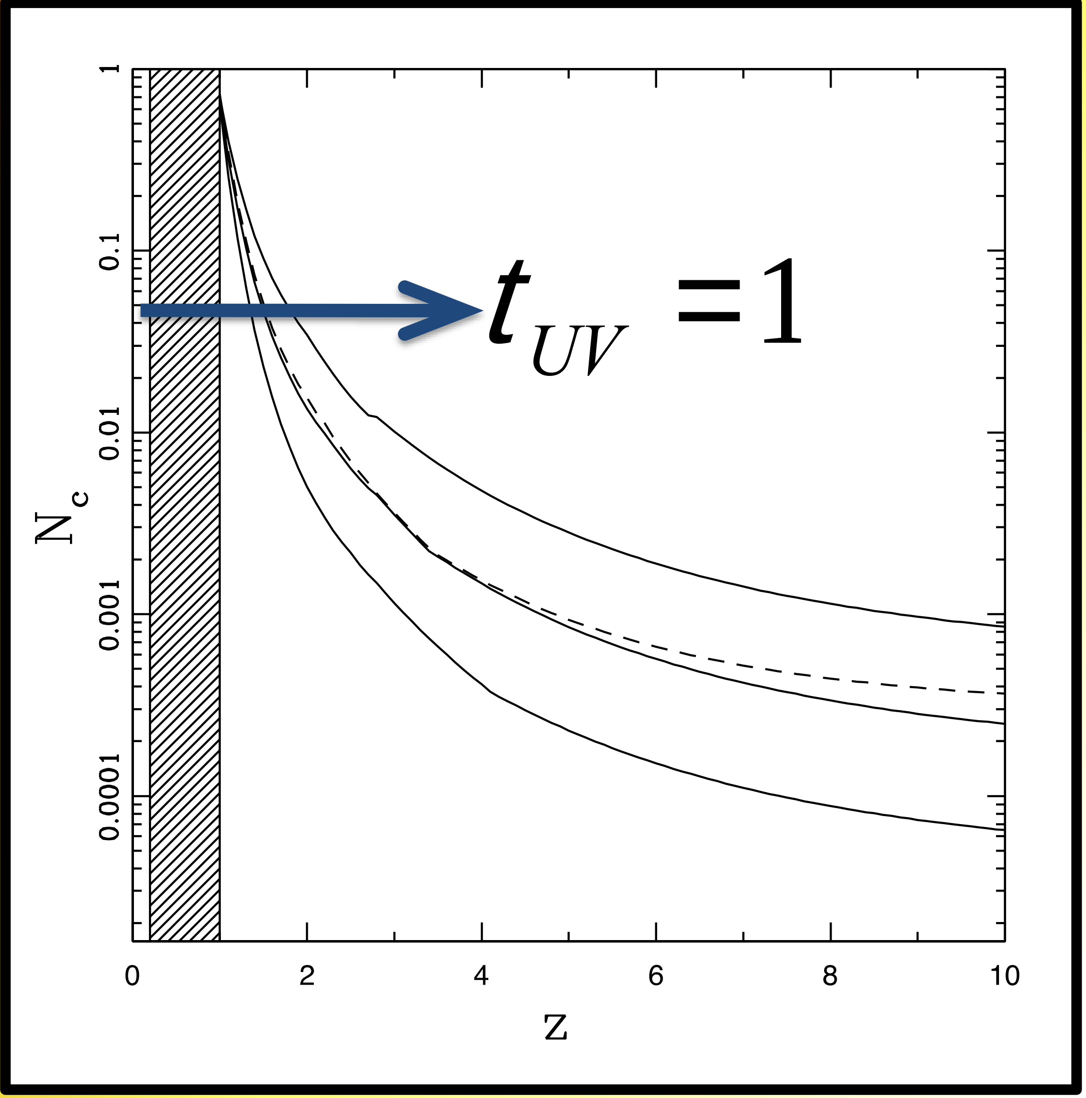
- Magnetic interactions can explain the observed synchrotron radiation in V773
- Interaction energy and benchmark power are simple functions of stellar and orbital properties => these ideas can be tested by studying a sample of T Tauri binaries
- Future work: predict synchrotron cutoff; brehmsstrahlung from particles hitting star; plasma breakout in interaction region; etc.

(Adams, Cai, Galli, Lizano, & Shu 2011, ApJ, 743, 175)

Analytic Dragons

- These coordinate systems only work for potential fields (no currents in region)
- The formalism has been developed for 2D systems; can work for 3D systems in principal, but complicated in practice
- Treatment is limited to steady-state magnetic fields and steady-state flow: magnetostatics not MHD

Column Density



Observational Implications