Three-dimensional Simulation of Disk-Magnetosphere-Stellar Wind Interaction in Protoplanetary System

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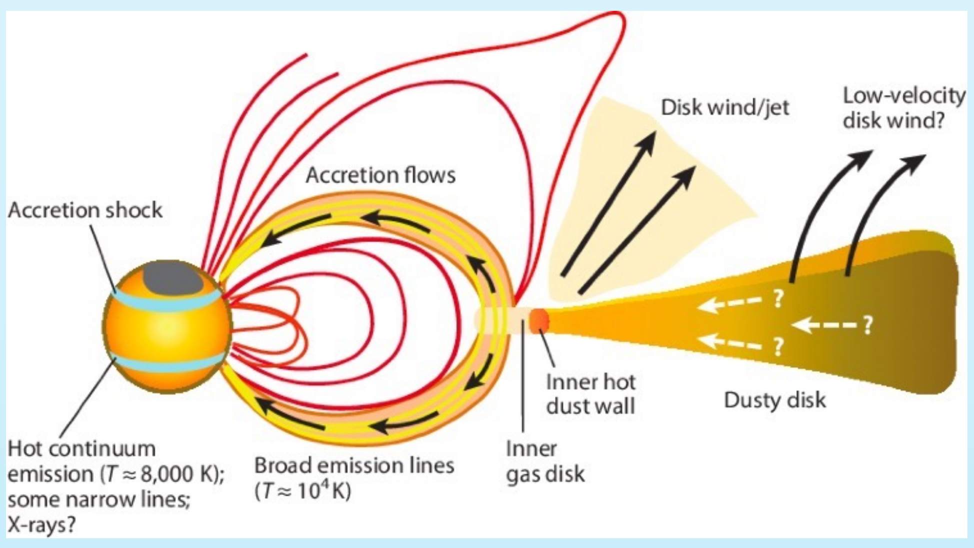
Conventional Paradigm

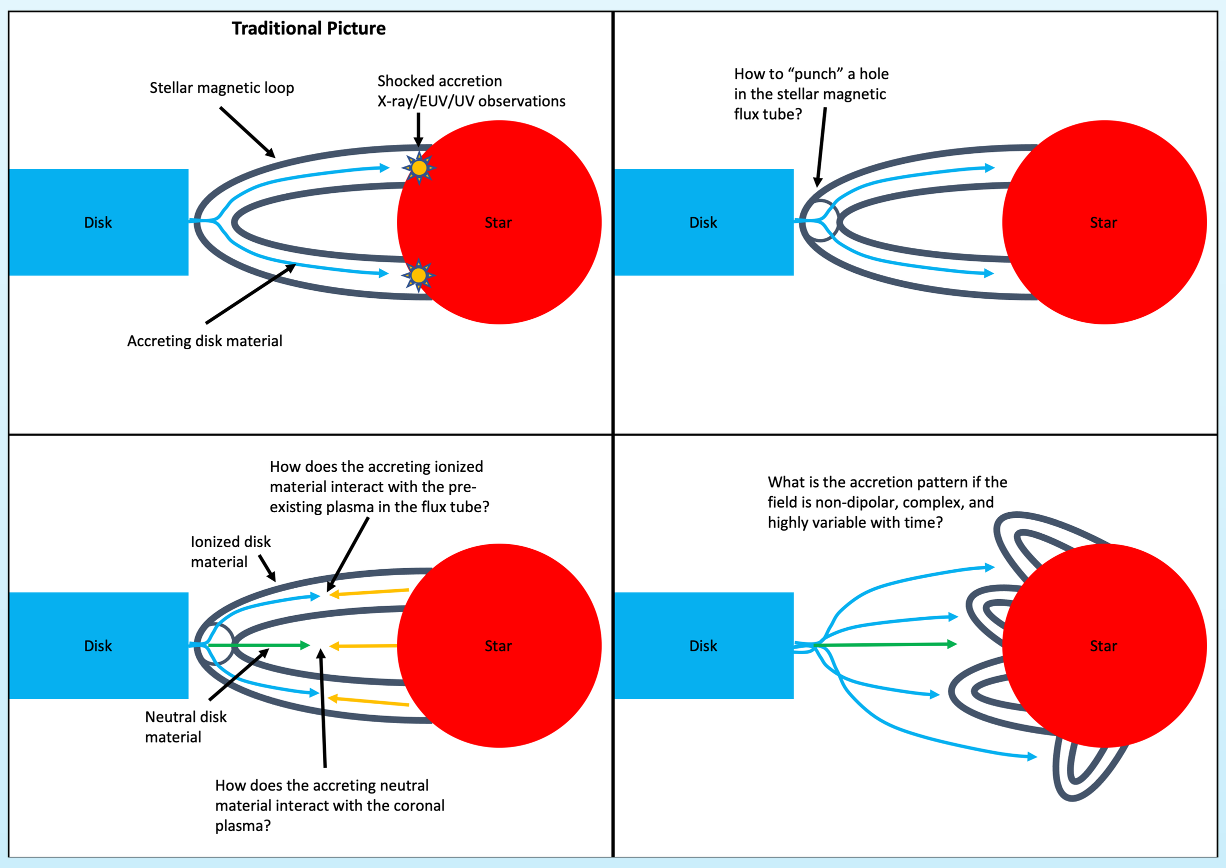
Traditional view of Disk-magnetosphere interaction in protoplanetary systems assumes that disk material accretes onto the star along closed magnetic loops. Infalling material is shocked and heated, producing Xray/EUV emissions that can be related to the accretion rate.



Hartmann, Herczeg, and Calvet 2016

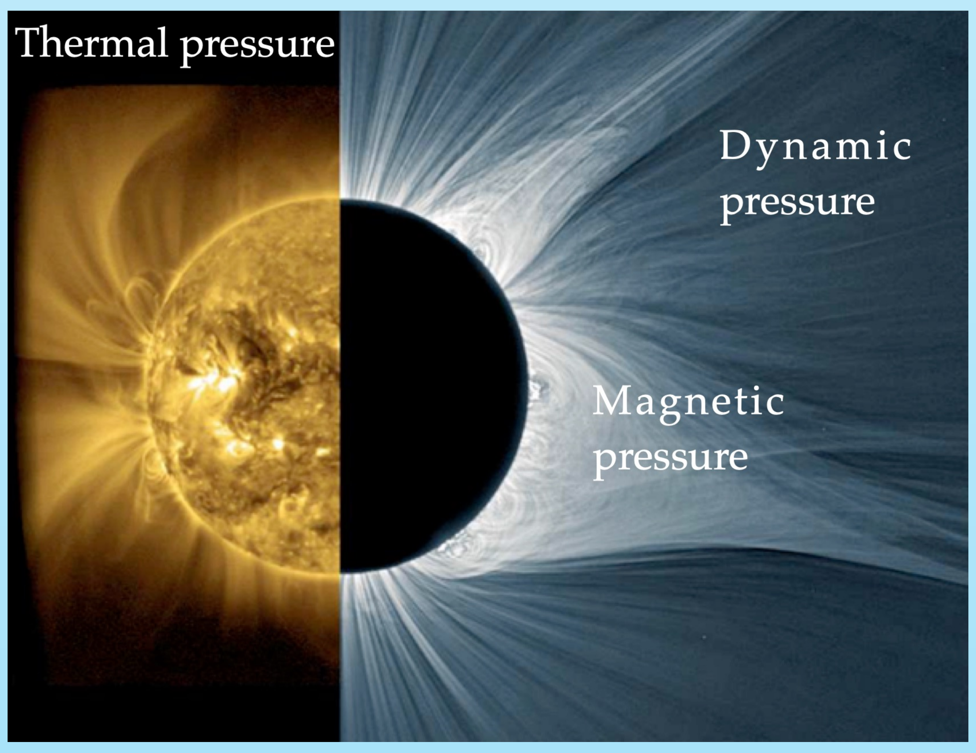
Challenges with the existing paradigm – An energized corona, not a static magnetosphere

- How can the accretion pattern be steady if the stellar field is complex, or non-steady?
- How does the disk material follow the coronal magnetic field lines (open or closed)? If it is neutral, it should not be affected by the magnetic field and simply fall onto the star, but if it is ionized, it needs to penetrate flux tubes.
- If the ionized disk material can penetrate flux tubes, then the pressure balance with the pre-existing plasma in the flux tube should be considered. It does not fall into an empty space all the way to the photosphere.
- What is the interaction between the accreting material and the coronal plasma and outflowing stellar wind? Can the coronal plasma and magnetic field impede the accretion flow to some extent?
- How are the accreting material and the coronal plasma/magnetic field coupled?
- Do observations of disk accretion represent steady, shocked accretion or could they be interpreted differently (e.g., sporadic accretion, coronal compression, or other disk-corona interaction)?



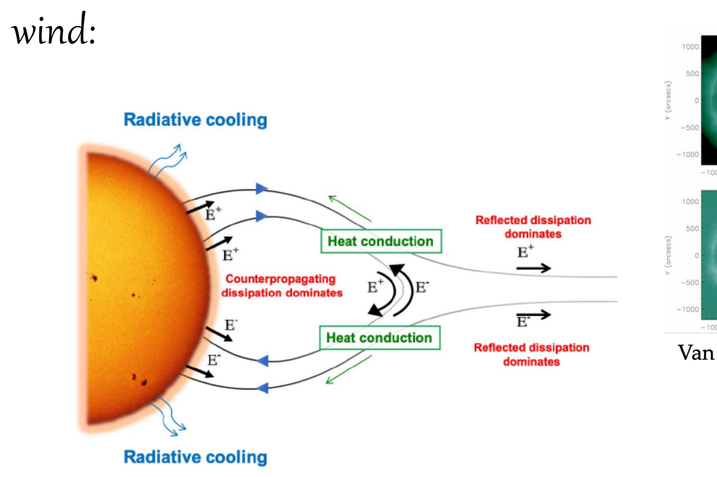
Energize Stellar Corona

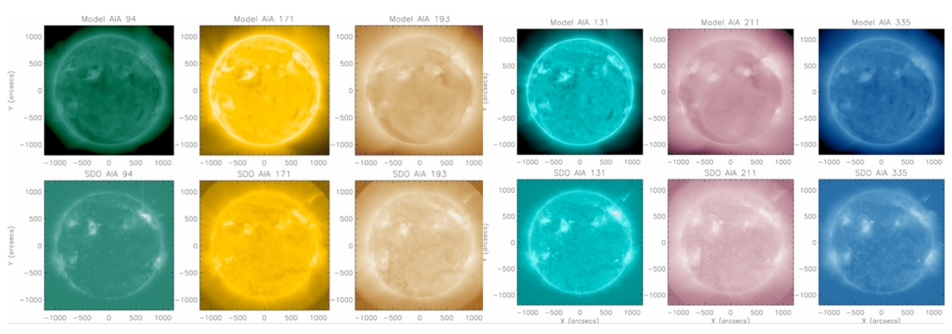
The medium between the disk and the star isn't just a static magnetic field, but it is an energized hot corona, with over 1M degrees Kelvin, and an accelerated stellar wind. Its combined pressure is the sum of the thermal, dynamic, and magnetic pressures, all oppose to the weight of the infalling disk material.



Modeling the Stellar Corona and Stellar Wind

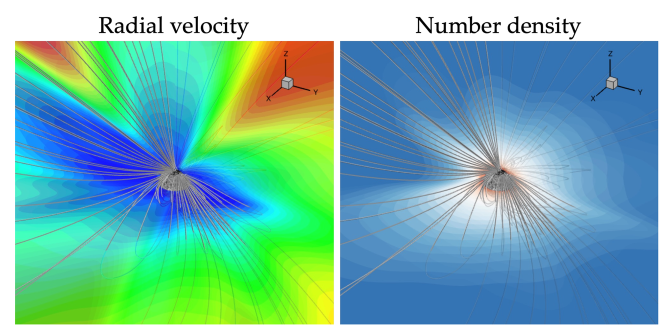
We use the AWSOM MHD model (Van der Holst et. al 2014) to simulate the stellar corona and stellar wind:

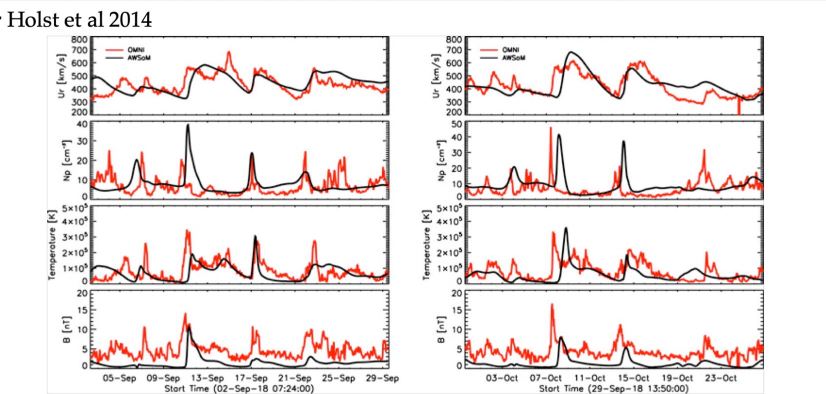




Van der Holst et al 2014

- Input (observations): photospheric magnetic field (magnetogram)
- Parameters:
  - The plasma distribution and the energy input at the inner boundary: density, temperature, Poynting flux, etc.
  - The parameters that determine how Alfven waves dissipate: correlation length, amplitude and exponent of the stochastic heating profile





Sachdeva et al 2019

Simulating Disk-corona Interaction

We superimpose a hydrostatic disk into the steady-state MHD solution and run it for 108h (one Keplerian rotation).

Stellar parameters:

Solar mass and radius, 45-degree tilted dipole with 100G equatorial strength (10 times solar)

Disk parameters:

Keplerian disk - maximum rotational velocity of ~ 200 km/s

Maximum density: 10^{13} cm^{-3}; Maximum disk temperature: 500 K

Hydrostatic disk properties:

Radial temperature: $T(R_e) = T_0/R_e$

Keplerian velocity: $\Omega_k(r) = \sqrt{2GM_*/r^3}$

Sound speed: $C_s = \sqrt{kT/m_p}$

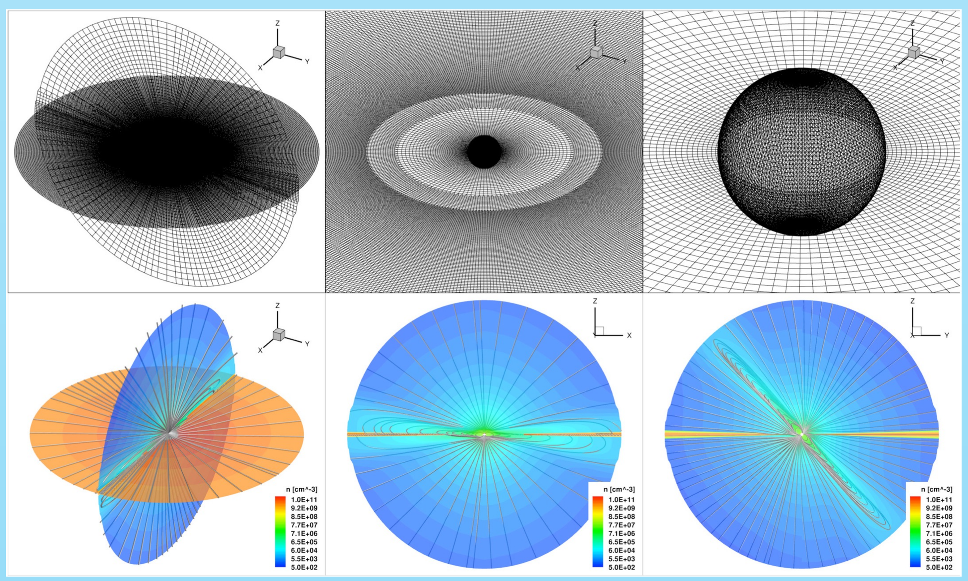
Disk scale height: $h = C_s/\Omega_k$

$$\rho(R_e, z) = \frac{1}{R_e}\rho_0 \exp(-|z|/h)$$

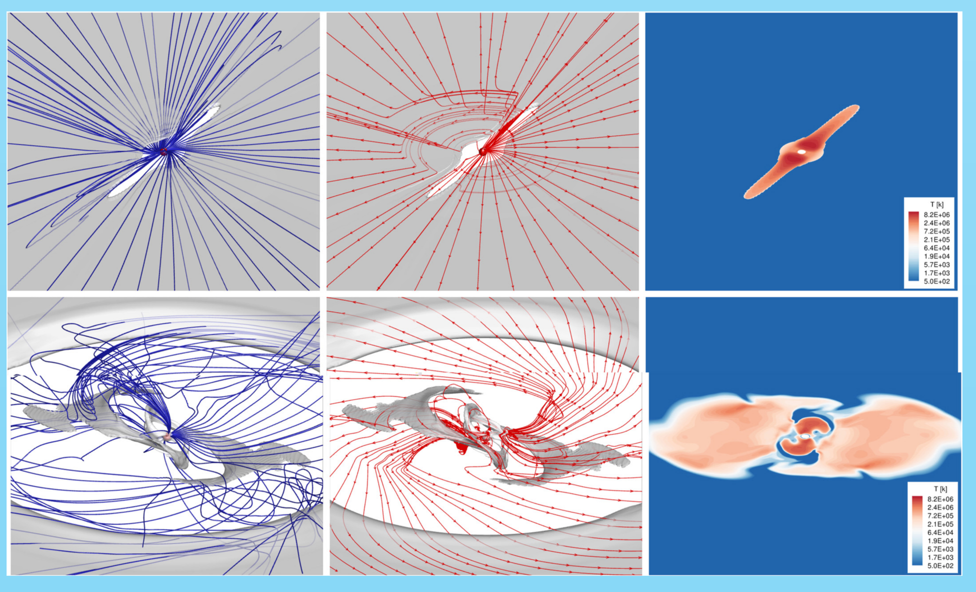
$$p(R_e, z) = \rho(R_e, z) C_s^2.$$

Imposed reduction of Keplerian velocity close to the star:

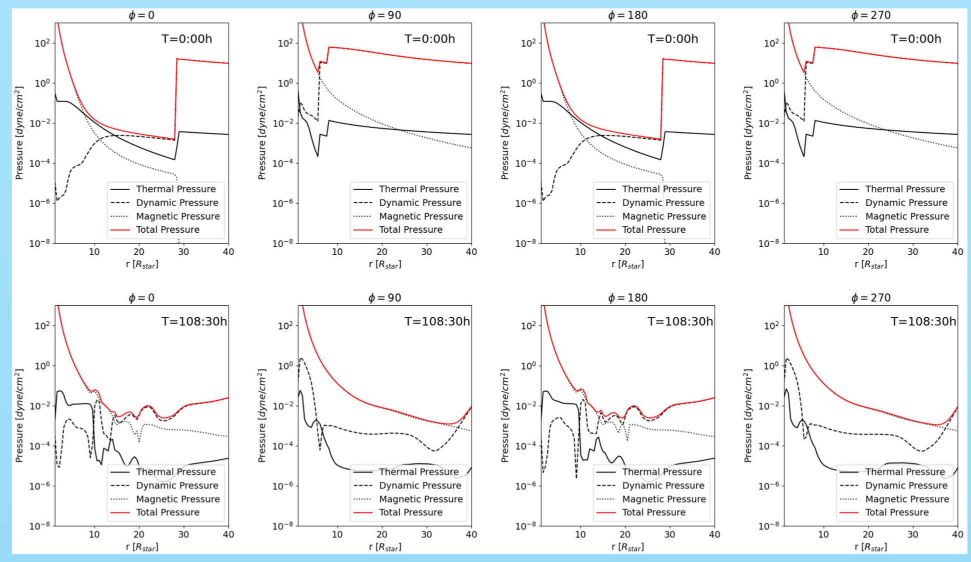
$$\eta(R_e) = 1{-}0.75*\exp(-R_e^2/10^2)$$



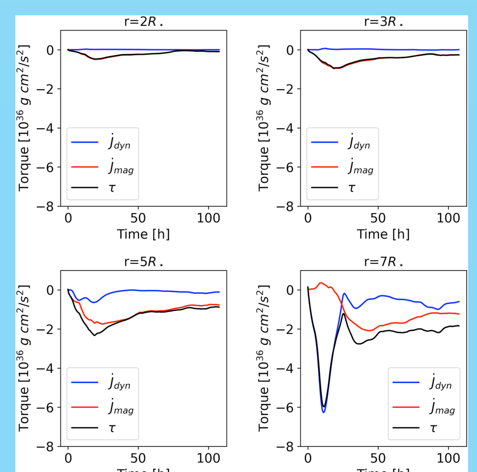
1. Siimulation grid and initial state after superimposing the disk in the corona MHD solution



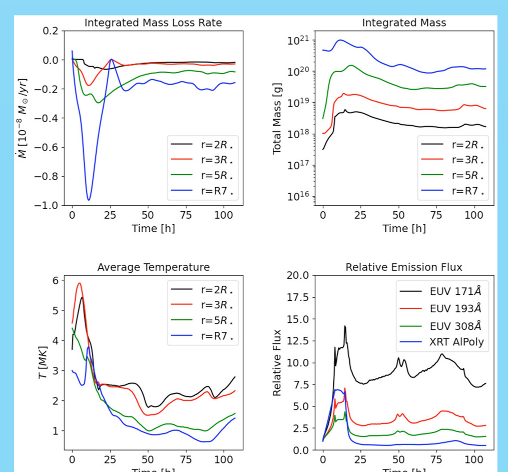
2. The three-dimensional structure of the disk–corona inner region as seen from 30 degrees above the equator. The left panel shows a white isosurface of n = 10^{10} cm^{-3}, which represents the higher-density region of the disk. The two initial gaps in the isosurface are due to the tilt of the stellar dipole field. The blue lines mark selected magnetic field lines that cover the displayed region. The middle panel shows the same isosurface with red-colored velocity streamlines. In the right panel, we show the equatorial plane colored with contours of the temperature, where blue regions mark the cold disk material and red regions mark the hot corona. These are sample snapshots for t = 0 (top panels) and t = 108 hr (bottom panels).



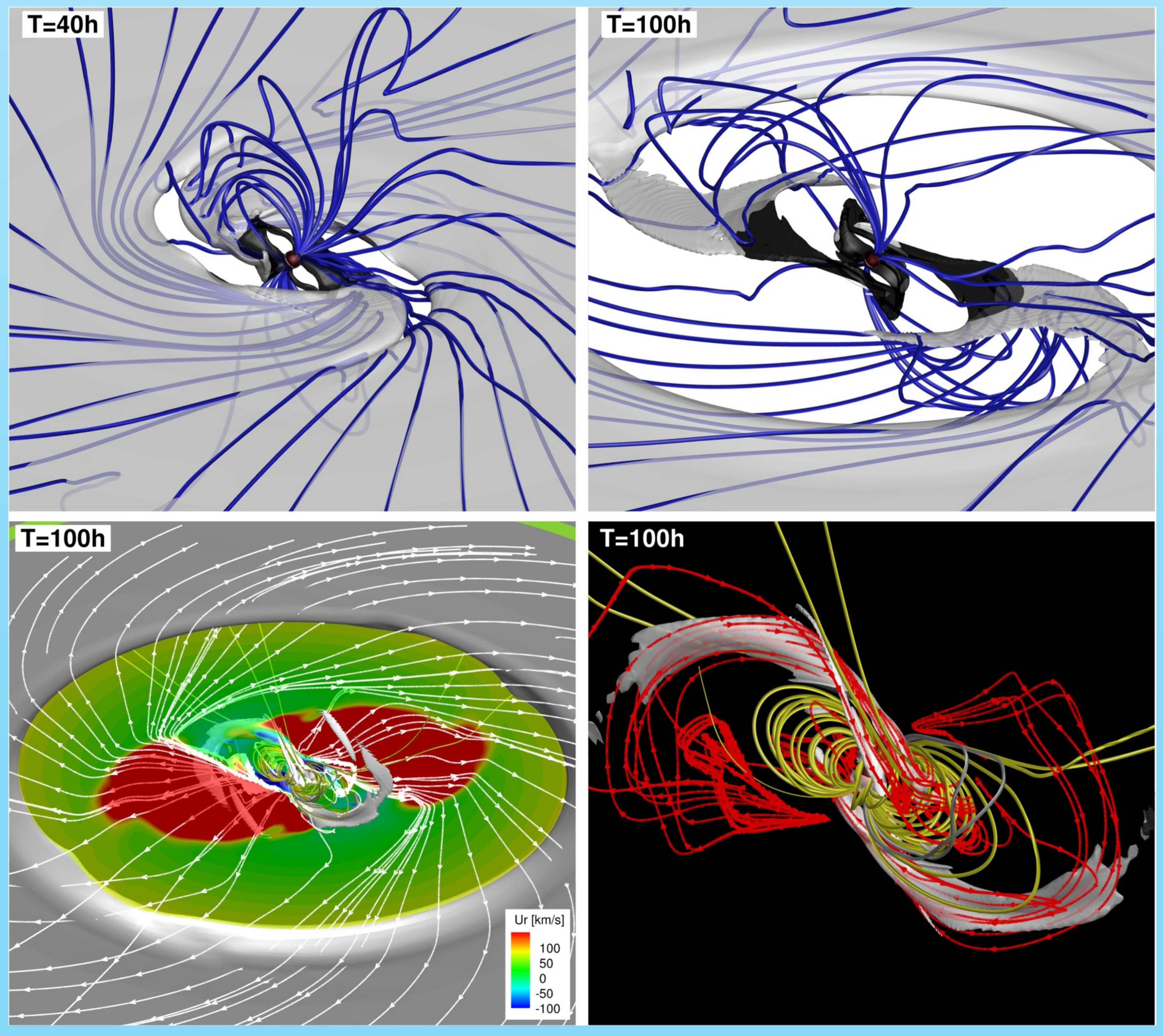
3. Temporal evolution of the radial distribution of the different pressure components as a function of distance from the star. The pressure components are thermal, dynamic, magnetic, and total. Plots show the radial distribution along extracted lines in the equatorial plane at four longitudes: 0 (first column), 90 (second column), 180 (third column), and 270 (fourth column) degrees. These are sample snapshots for t = 0 (top panels) and t = 108 hr (bottom panels).



4. The different components of the torque - dynamic (blue), magnetic (red), and total (black), as a function of time. The torques are integrated over spheres at r = 2Rstar (top left), r = 3Rstar (top right), r = 5Rstar (bottom left), and r = 7Rstar (bottom right).



5. Integrated values on four spheres at r = 2 (black), 3 (red), 5 (green), and 7 (blue) Rstar as a function of time. The plots are for the mass-loss rate (top left), integrated mass (top right), temperature (bottom left), and integrated synthetic emission flux (bottom right).



6. Top: density isosurface of n = 10^{10} cm^{-3} along with selected magnetic field lines shows the region close to the star at t = 40 hr (left), and t = 100 hr (right). Bottom left: isosurface of n = 5x10^{10} cm^{-3} along with a z = 0 slice colored with the radial velocity contours at t = 100 hr. White lines represent selected velocity streamlines. Bottom right: a zoom at the vicinity of the star at t = 100 hr shows selected coronal magnetic field lines in yellow, selected velocity streamlines in red, and an isosurface of vr = −30 km s^{-1}.

The Bottom Line

We present a three-dimensional simulation of the short-term interaction of the protoplanetary disk and the stellar corona. Our simulation includes the disk, the stellar magnetic field, and self-consistent coronal heating and stellar wind acceleration. Our main findings are: 1) At the beginning of the simulation, when the system relaxes from its artificial initial conditions (the first 25 hr), the inner part of the disk winds around and moves very close to the star in what seems to be a strong accretion. However, after about 30 hr, the corona begins to build up its original state. This pushes the disk out until the disk–corona boundary is beyond 10Rstar.=; 2) A strong, steady disk accretion that is funneled along coronal field lines is not clearly visible at any stage of the simulation. Instead, very weak, sporadic accretion is observed; 3) We produce synthetic line emission light curves that show flare-like increases during the time of the simulation. These flux increase events are not correlated with accretion events nor with heating events. Our simulation points to variations in the line emission flux being the result of coronal compression and extraction due to the disk–corona pressure variations; and 4) The disk wind evolves above and below the disk. However, the disk–stellar wind boundary stays quite stable, and any disk material that reaches the stellar wind region is advected out by the stellar wind.

Reference: Cohen et. al, The Astrophysical Journal, Volume 949, 15; **Contact:** ofer_cohen@uml.edu