Rotation of pre-main-sequence stars

Angular momentum problem of star formation. Consider a molecular cloud core with $R \sim 0.1$ pc, $M = M_\odot$, and angular velocity $\Omega = 10^{-14}\ \mathrm{s}^{-1}$.

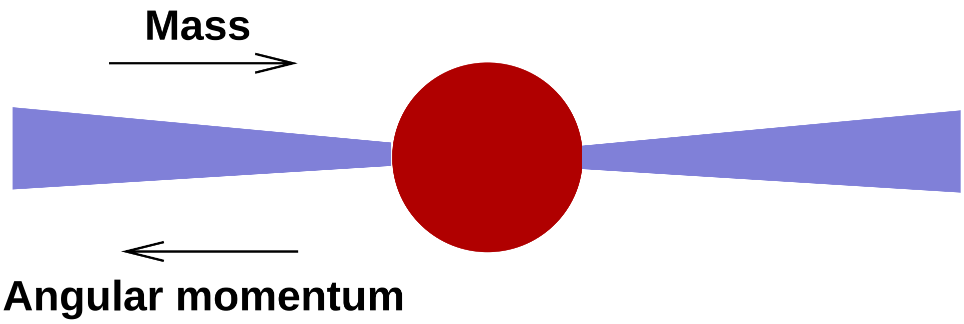
- Gravitational energy $GM^2/R = 10^{42}$ erg, rotational energy $(1/2)I\Omega^2$ with $I = k^2MR^2$ is 4×10^{39} erg ($k^2 = 2/5$). Rotational energy is completely negligible (less than 1%).
- Angular momentum $J = I\Omega = 7 \times 10^{53}\ \mathrm{g\ cm^2\ s^{-1}}$.
- Typical T Tauri rotational period is a week. Taking radius to be $3\ R_\odot$, estimate $J = 2 \times 10^{50}\ \mathrm{g\ cm^2\ s^{-1}}$ ($k^2 = 0.2$).
- For the Sun, rotation period is about a month, and $J = 2 \times 10^{48}\ \mathrm{g\ cm^2\ s^{-1}}$ ($k^2 = 0.1$).

Almost all the cloud's angular momentum must be lost to form a T Tauri star.

A further large fraction of the angular momentum must be lost during subsequent stellar evolution.

Role of disks

Most of the mass of protostars may be accreted via a disk.



Disk transports most of the angular momentum to large radius (and / or ejects it in an outflow), partially solving the problem:

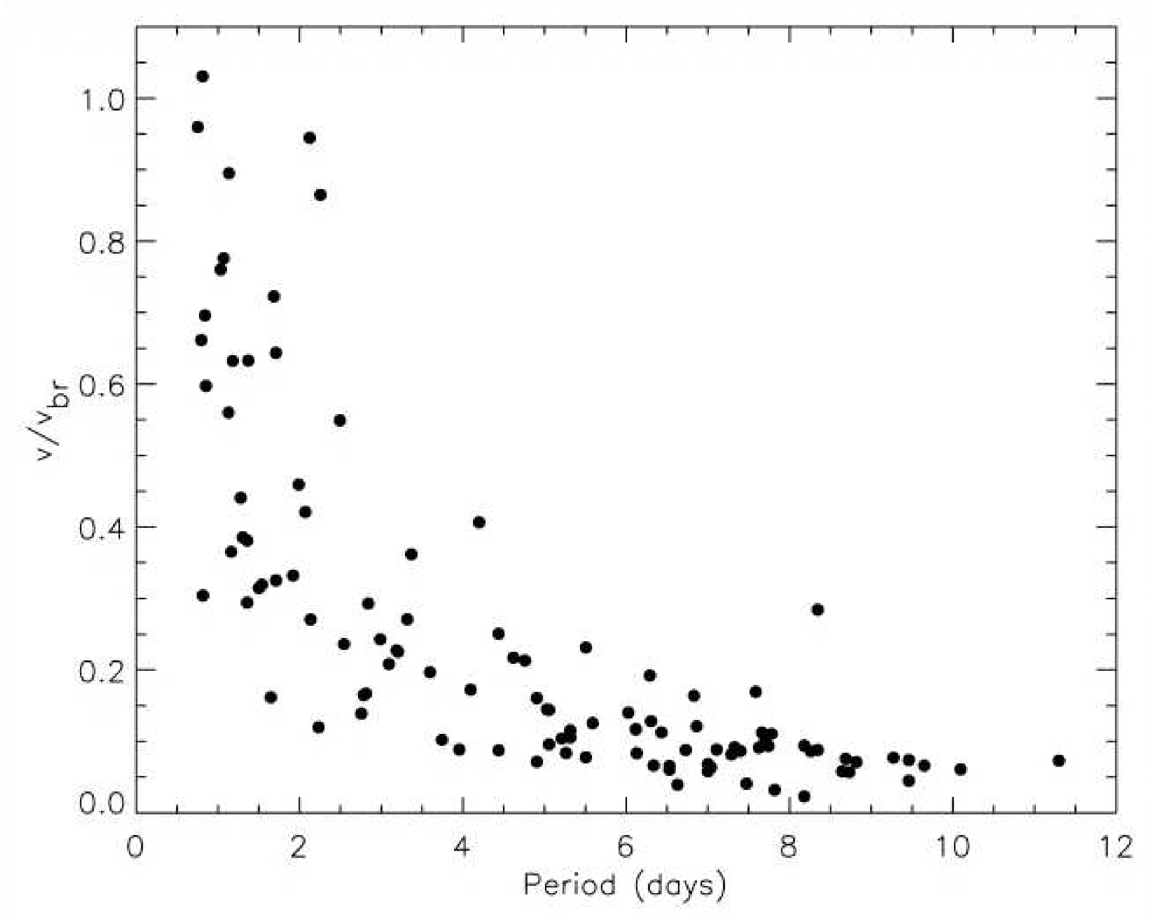
- For cloud core, $J/M = 4 \times 10^{20}$ cm^2 s^{-1}.
- Gas accreted with Keplerian specific angular momentum at $R = 3\ R_\odot$ has $J/M = 5 \times 10^{18}$ cm^2 s^{-1}.

But, still need to explain why,

- Accretion of gas at 'break-up' velocity +
- Continuing contraction

...does not yield stars spinning at close to break up velocity.

Rotation periods for stars in the Orion nebula cluster determined via photometric monitoring (Stassun et al., 1999, AJ, 117, 2941):



Some stars rotating near breakup, but most are at ~ 0.1 breakup velocity.

Even ignoring accretion, relatively slow rotation requires efficient angular momentum loss. eg radius and radius of gyration for solar mass pre-main-sequence models:

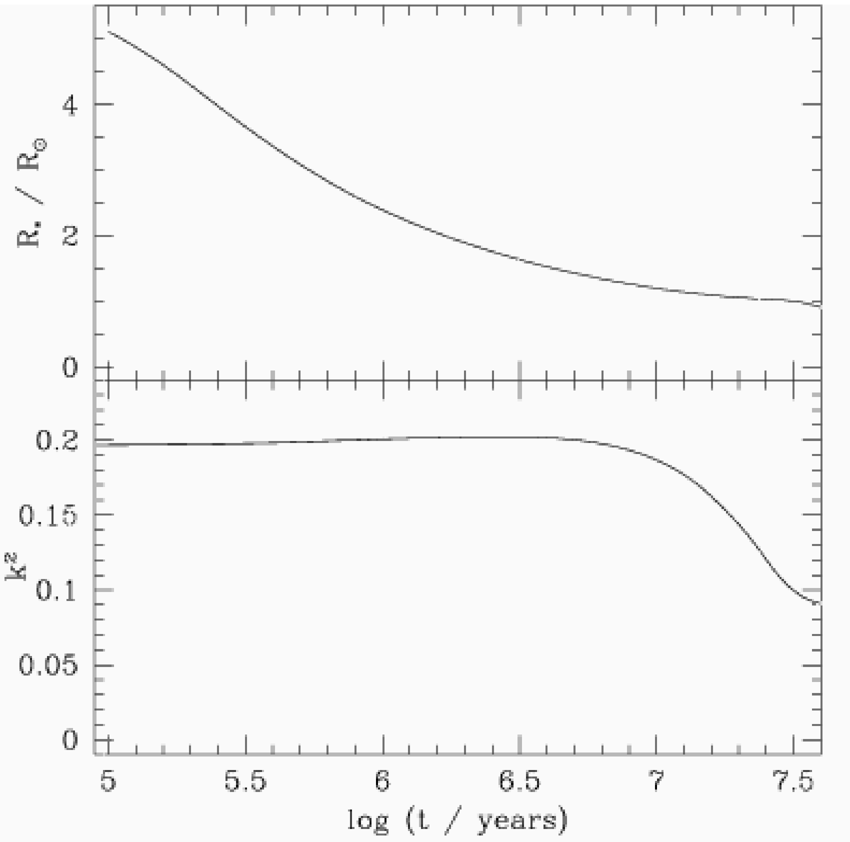


Figure 1. Evolution of the stellar radius R_* and squared radius of gyration k^2 for the 0.9985 $M_\odot$ stellar model.

Between 1 Myr and 30 Myr, roughly order of magnitude drop in moment of inertia.

Alfven radius

Some T Tauri stars have measured surface magnetic fields of the order of 1 kG. Does this influence the accretion flow?

Consider a dipole field,

$$B(R) = B_0 \left(\frac{R_*}{R} \right)^3$$

and compare the magnetic energy density with the kinetic energy density of inflowing gas (for now assumed to be spherically symmetric and in free-fall). Equality when,

$$\frac{B^2}{8\pi} = \frac{1}{2}\rho v^2$$

where,

$$v = \left(\frac{2GM}{R} \right)^{1/2}$$

and,

$$\rho = \frac{\dot{M}}{4\pi v R^2}.$$

Obtain an expression for the Alfven radius,

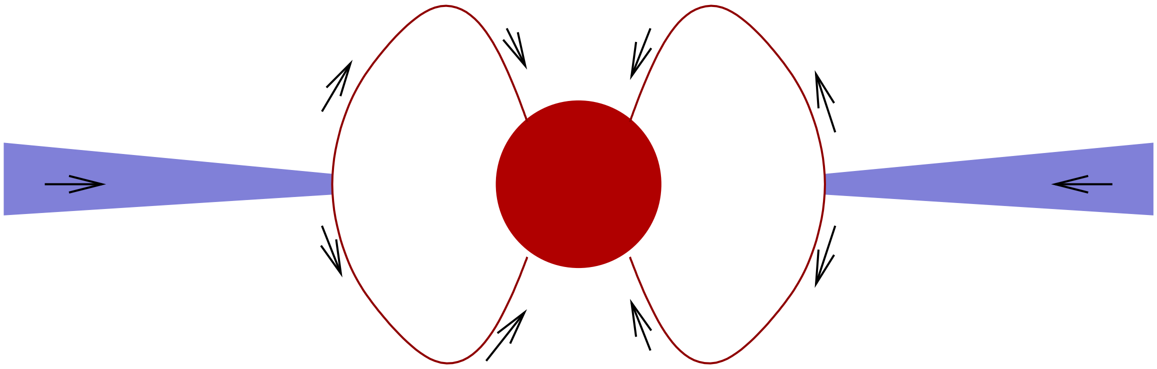
$$R_A = \left(\frac{B_0^2 R_*^6}{\dot{M}\sqrt{2GM}} \right)^{2/7}$$

For Classical T Tauri parameters,

$$R_A = 13\ R_\odot \left(\frac{B_0}{1\ \mathrm{kG}}\right)^{4/7} \left(\frac{R_*}{2\ R_\odot}\right)^{12/7} \left(\frac{\dot{M}}{10^{-8}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-2/7}.$$

Non-spherical accretion (via a disk) changes this answer by a numerical factor of the order of unity.

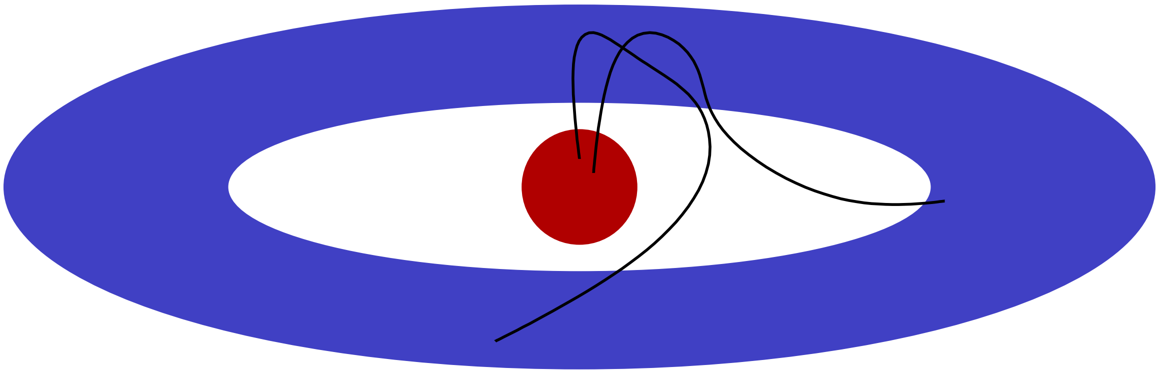
Conclude: T Tauri magnetic fields dominate the accretion flow within the innermost few stellar radii $\rightarrow$ magnetospheric accretion.



Gas in magnetically dominated region is expected to follow the field lines and strike star in a free-falling accretion column.

Several observational clues that this geometry is roughly correct.

Magnetic torque on star:



Field lines linking the star to the disk:

- Act to slow down disk gas (spin up star) if $\Omega_K > \Omega_*$.
- Act to speed up disk gas (spin down star) if $\Omega_K < \Omega_*$.

Critical dividing radius is the corotation radius,

$$R_c = \left(\frac{GM}{\Omega_*^2} \right)^{1/3}$$

which is at 15 $R_\odot$ for a solar mass star with a rotation period of a week.

$\rightarrow$ magnetic fields of pre-main-sequence stars may disrupt disk close to the corotation radius.

Coupling of the star to the disk *outside* R_c allows the star to lose spin angular momentum to the disk.

Magnetic torque per unit area of disk surface is,

$$T = \frac{B_z B_\phi R}{2\pi}.$$

Assume area torque acts on is $\sim \pi R_c^2$.

Take $R_c = 10\ R_\odot$, $B_z = B_\phi = 10$ G at this radius.

Infer $T \sim 2 \times 10^{37}$ g cm^{-2} s^{-2}. Acting over 1 Myr, can lose 5×10^{50} g cm^{-2} s^{-1} of stellar angular momentum to the disk.

$\rightarrow$ more than enough to maintain slow rotation of a classical T Tauri star as long as the disk remains present.

'Magnetic disk locking' model. Predictions:

- Stars should have disks disrupted close to the corotation radius (if not, spin up torque from gas inside R_c rapidly wins).
- Stars should be braked as classical T Tauri stars, but spin up once they lose their disks.

Numerical models differ in sophistication of,

- Structure of magnetic field.
- Consistency of coupled disk evolution.
- Inclusion of non-solid body stellar rotation.

General agreement that it can work,

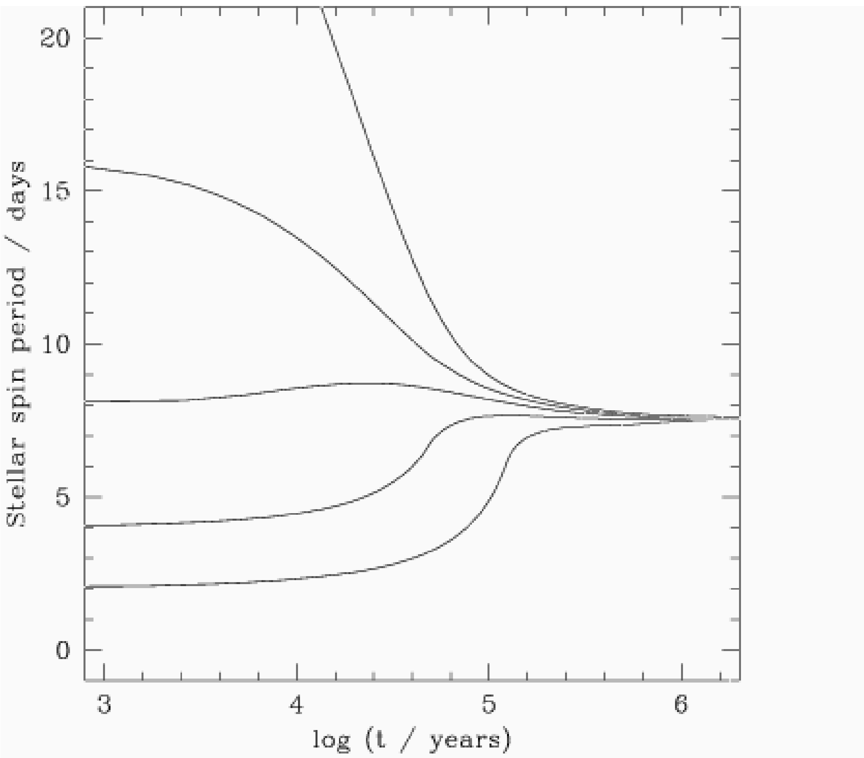


Figure 3. The evolution of rotation period for models with differing initial rotation period, here taken in the range 2-32 dy.

...regardless of initial rotation rate (Armitage & Clarke, 1996).

Provided that the disk is massive enough,

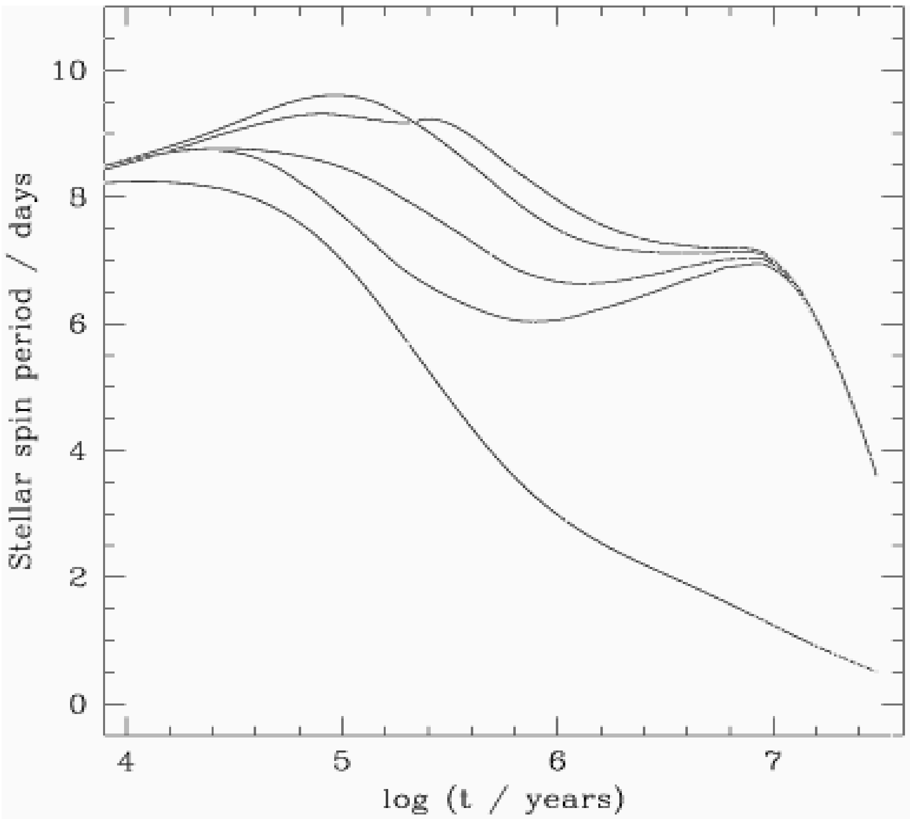


Figure 5. Time-dependence of the stellar spin period for models computed with different initial disc masses. In all cases the outer boundary was appropriate for a 'single' star and was set at 20 a.u. From top downwards at $t = 10^6$ yr the curves represent $M_{\rm disc} = 3\times10^{-3}, 10^{-2}, 3\times10^{-2}, 10^{-1}$ and $10^{-3} M_\odot$ respectively.

Clear that stellar winds also play a role, but how important at this early epoch unclear.

Accreting X-ray pulsars

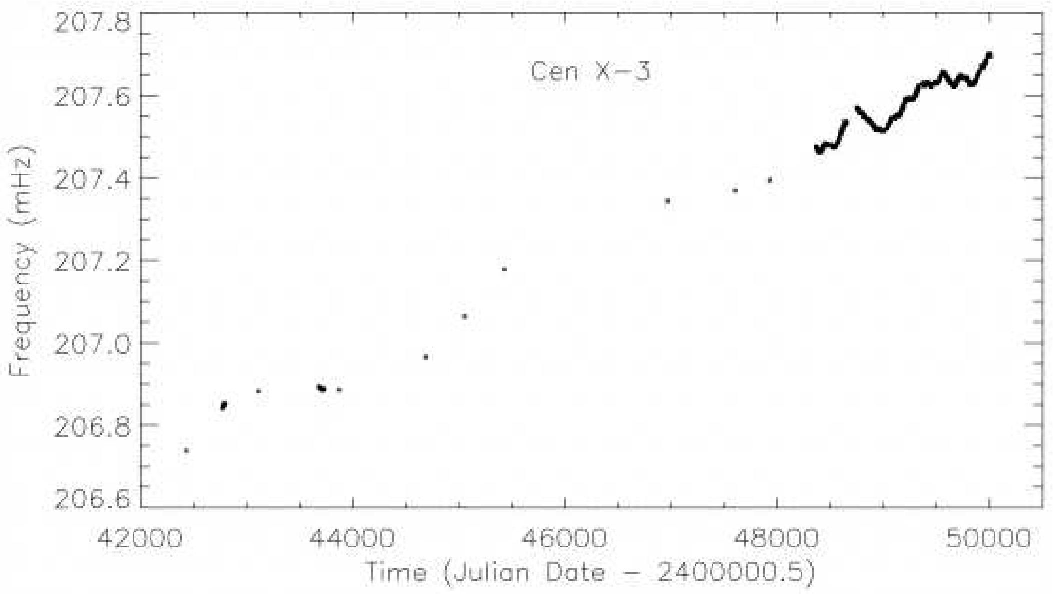
Prototypes of accreting magnetized stars:

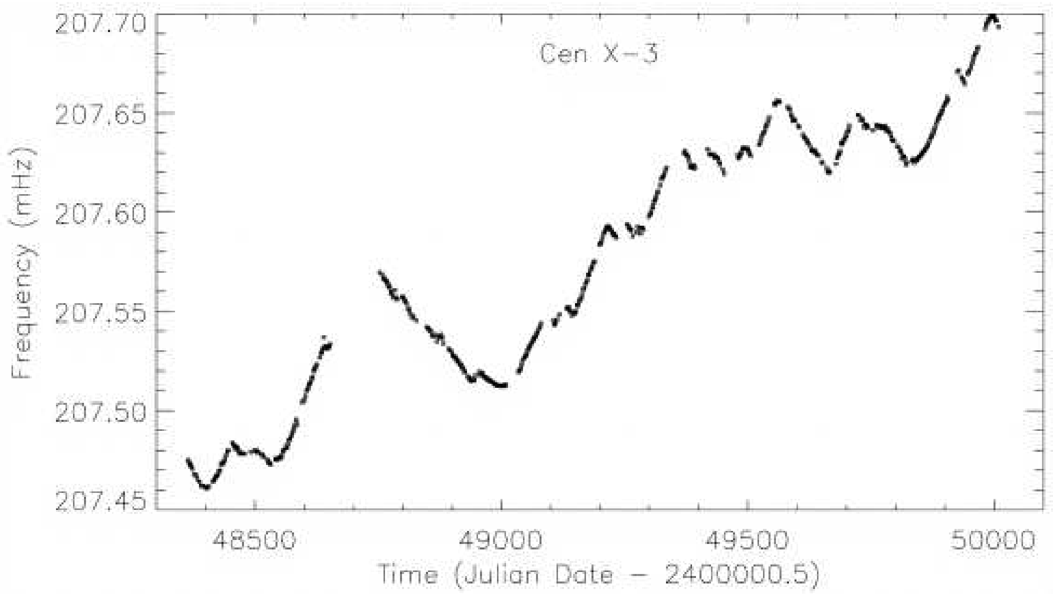
- Rotating, strongly magnetized (10^{11} G) neutron stars.
- Accreting gas from a disk or wind fed by a stellar companion.
- Accreting gas is funnelled to hotspots near poles $\rightarrow$ pulsed X-ray or γ-ray emission.

Accurate timing allows measurement of the rate of change of the rotation rate $\rightarrow$ estimate of accretion torque.

BATSE provided well-sampled spin histories for the first time (Bildsten et al., 1997, ApJS, 113, 367).

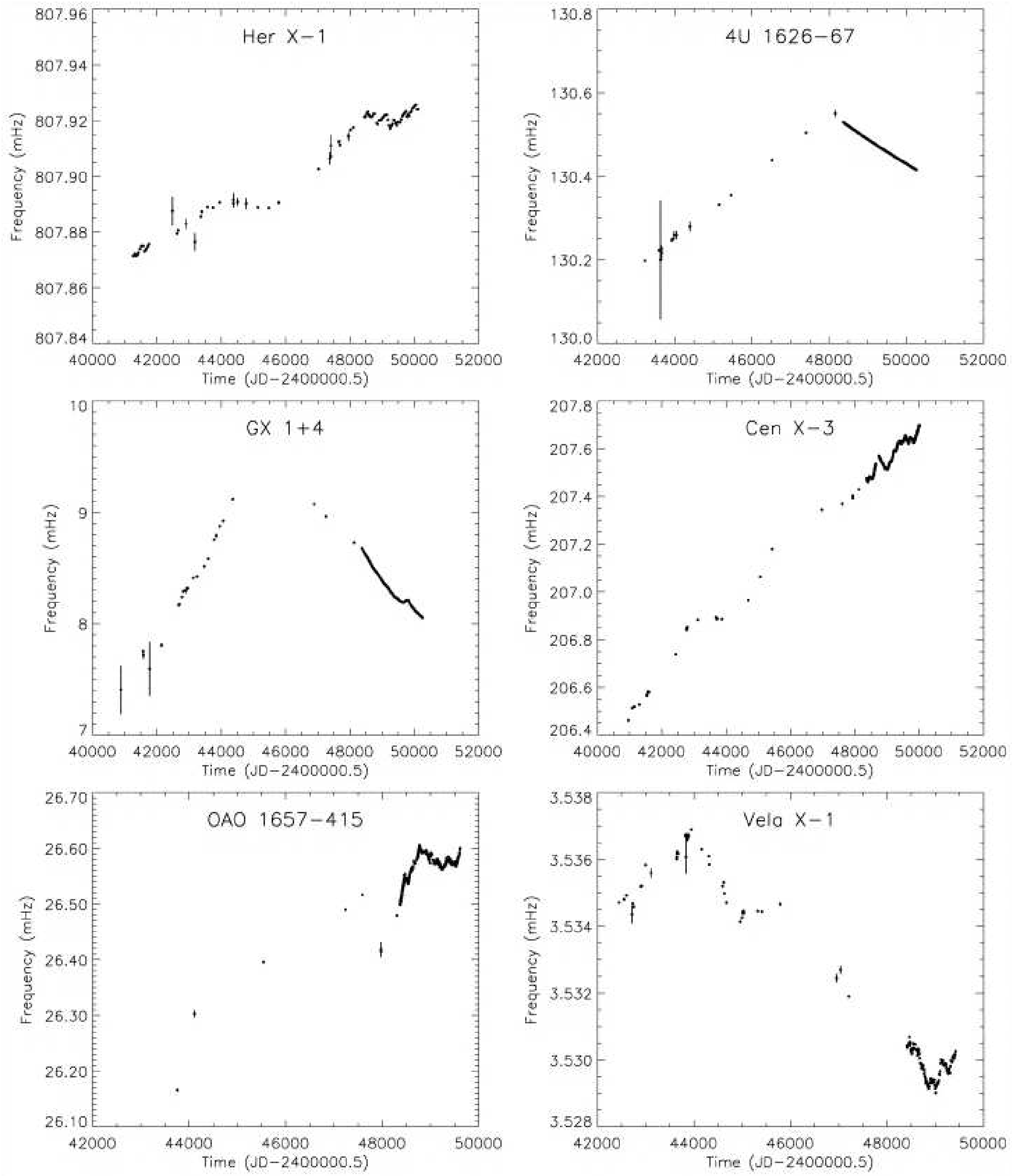
Long term spin history of Cen-X3:





Sign of the accretion torque reverses on short timescales!

Common among other monitored systems:



Torque and luminosity are not always correlated as expected based on simple theory (Chakrabarty et al. 1997, ApJ, 481, L101).