Angular Momentum Loss Considerations in Large Scale T Tauri Flares

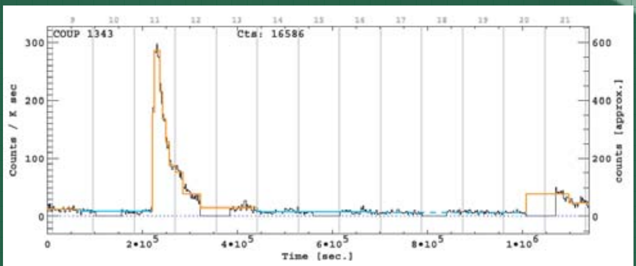
A. N. Aarnio K. G. Stassun Vanderbilt University

Abstract

The Chandra Orion Ultradeep Project observed a number of T Tauri stars during highly energetic X-ray flare events. Favata et al. (2005) applied a uniform cooling loop model effective in modeling solar magnetic field loops to derive loop arc lengths on the order of tens of stellar radii. In the context of pre-main sequence evolution, are we to interpret these loops as structures connecting star to disk or, using a solar analogue, do they represent extreme "coronal mass ejections" (CMEs)? We have created Monte Carlo models of the spectral energy distributions of the stars with the largest flaring loops and found that the majority of the sample appears to lack circumstellar disk material. This surprising result is the impetus for detailed analysis of the mass and angular momentum lost via CME events of this magnitude. We present estimates of angular momentum loss via large scale flare events and discuss the implications of this work for stellar angular momentum evolution of young low-mass stars.

Motivation for study

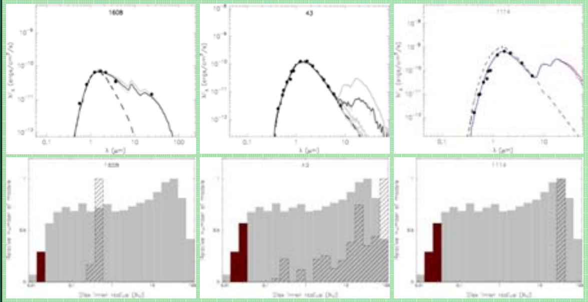
Targets from this study were found within a larger set of data taken as part of the COUP (Chandra Orion Ultradeep Project). These 32 targets are among ~1600 sources in the ONC observed in the X-ray regime; they are of particular note because they show huge increases in X-ray flux over relatively short timescales. Although transient events, magnetic field lines must exist at scales such that they can reconnect and produce the observed phenomena. This has many implications for pre-main sequence evolution, including star-disk interaction, and the shedding of angular momentum.



Light curve of COUP 1343 from Favata et al. (2005). The sharp increase in flux implies impulsive, rather than sustained, heating. The loop parameters are derived from analysis of the flare decay.

Do Large Flares Represent Star-Disk Interaction or CMEs?

A census was performed of all the large scale flaring candidates for disk indicators, specifically, Spitzer IRAC and MIPS near-mid IR fluxes (Aarnio & Stassun, 2007). Spectral energy distributions were created using the T Tauri Star Radiative Equilibrium (TTSRE, Whitney et al. 2003) Monte Carlo model fitter of Robitaille, et al., 2006. Approximately one fourth of the sample appeared to have excess indicative of disk presence, and of those, only two stars' modeled truncation radii were coincident with the magnetic loop length. Our results imply that a star-disk connection is, generally, not occurring in this sample, which begs the question of the role played by the large scale flares.

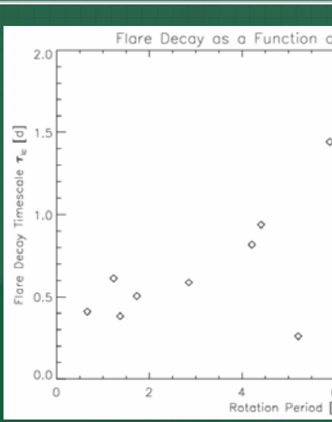


$R_{loop} = 3.3\ R_\star$, $R_{trunc} = 51.6\ R_\star$ | $R_{loop} = 5.5\ R_\star$, $R_{trunc} = 397\ R_\star$ | $R_{loop} = 9.77\ R_\odot$, $R_{trunc} = 82.6\ R_\odot$

Sample SEDs for three COUP stars. Dashed lines indicate solely stellar photosphere; red/blue/gray lines indicate disk models. Fluxes are from Hubble ACS photometry, the Hillenbrand (1997) survey V and I band data, 2Mass JHK, and Spitzer IRAC/MIPS.

The histograms show in red the radius of the flaring loop structure, in hatched bins the model disk truncation radii (were a disk indeed present), and the gray bins show the distribution of truncation radii available in the model grid.

For most of the sample, infrared excess indicative of a disk was absent. The vast majority of the sample is naked T Tauri stars with large flaring loops, i.e., extreme CMEs.



For 13 sample stars with known rotation rates, it is interesting to speculate as to the relationship between the flaring loop structure's decay and the stellar rotation rate. In spite of low sample number, the physical reason for this result could be that more slowly rotating stars "break up" these transient loops more slowly, which gives the loops more time during which to shed mass and angular momentum.

The Calculations

We begin by defining the density within the flaring loop based on X-ray light curve derived parameter, n_e, and assuming a plasma of ionized H with negligible mass electrons:

$$\rho = n_e m_p \tag{1}$$

As per Favata *et al.* (2005), a loop volume is defined as:

$$V_{loop} = 2\pi\beta^2 l^3 \tag{2}$$

where β is defined as $\frac{r}{l}$, the ratio of loop radius to arc length. Typically in solar flares, $\beta = 0.1$.

$$M_{loop} = \rho\, V_{loop} \tag{3}$$

For a steady state wind, the angular momentum in the loop is defined:

$$J_{CME} = M_{loop}\, \omega\, r_A^2 \tag{4}$$

where r_A is the Alfvén radius, where material in the loop is effectively corotating with the star (Weber and Davis 1967). It is typically twice the loop height (Mestel and Spruit 1987; Matt and Balick 2004) which we take to be half its length:

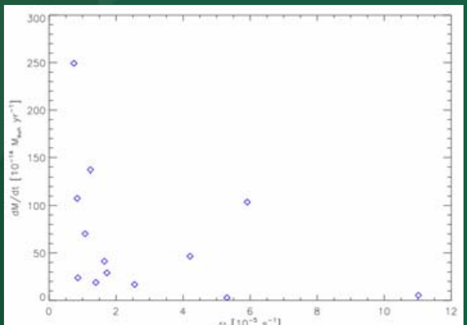
$$r_A = R_{star} + 2\frac{l}{2} = R_{star} + l \tag{5}$$

The rates of mass loss and thus angular momentum loss can be expressed as:

$$\dot{M}_{loop} = M_{loop}\, N_{events} \tag{6}$$

This expression ultimately depends on the number of large scale flaring events occurring over time.

$$\dot{J}_{CME} = \dot{M}_{loop}\, \omega\, r_A^2 \tag{7}$$



The flare decay time increasing as a function of increasing rotation period implies that slower rotators will lose more mass per event than more rapidly rotating stars. The above plot supports that idea: independently measured quantities, mass loss rate (from X-ray flare decay) and rotation rate (from photometric surveys) appear to be related. Here, an event rate of 1 CME per year is assumed.

ω [10^{-5}s^{-1}]	dM/dt [10^{-14} $M_\odot$ yr^{-1}]	dJ/dt [g AU^2 s^{-2}]
1.6	41.3	971,003
5.3	2.88	26,418
0.8	23.8	265,503
0.7	249	65,688,220
1.4	18.9	196,417
2.6	16.8	563,141
1.1	70.3	2,751,773
1.7	29.1	1,262,288

A table of rotation rate, mass loss per year (assuming 1 CME event per year) and resulting angular momentum loss rate. Only 8 sample stars had all parameters necessary for J calculation (M_*, R_*, ω).

For comparison purposes,

$$\dot{M}_\odot \sim 10^{-14}\ M_\odot\ \mathrm{yr}^{-1} \tag{8}$$

(Via solar wind.)

$$\dot{J}_\odot \sim 10^{30}\ \mathrm{dyn\ cm} = 4,468\ \mathrm{g\ AU^2\ s^{-2}} \tag{9}$$

as per Li (1999).

Conclusions

Our preliminary results indicate the possibility that CME like events could play a non-negligible role in pre-main sequence angular momentum evolution. In comparison to the angular momentum lost annually via the solar wind, one large scale CME event can shed up to five orders of magnitude more angular momentum. Future work will include a more sophisticated event number and energy distribution, as well as considerations of the time evolution of other parameters (ω, r_A, R_*).

As we work to quantify this effect, we find interesting relationships. Larger sample sizes are needed, but initially it would appear that slower rotators will shed more mass and angular momentum in an event than faster rotators; this implies a steeply decreasing slope in an angular momentum evolution function toward later times.

The authors would like to acknowledge S.P. Matt for his invaluable contributions to the process of making these calculations. K.G.S. acknowledges NSF Career Grant AST-0349075.