X-ray flares, coronae and disks in Orion young stars

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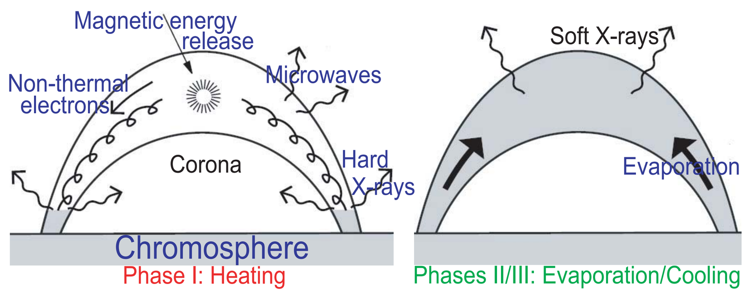
ABSTRACT

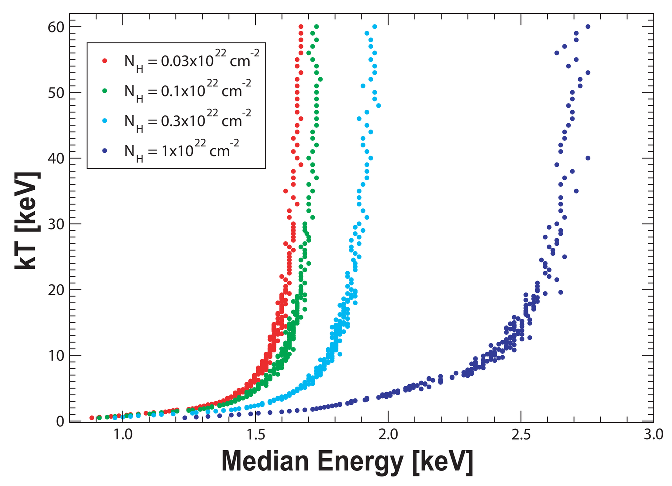
Pre-main sequence (PMS) stars are known to produce powerful X-ray flares which resemble magnetic reconnection solar flares scaled by factors up to 10^4. Several puzzles are present: the stability of implied magnetic loops ~10 times the stellar radius; possible magnetic loops extending to the protoplanetary disk; and the origin of slow-rise flares. To investigate these issues in detail, we examine >200 of the brightest flares from >160 COUP stars which constitute the largest known homogeneous dataset of PMS flares ever acquired. We use an innovative method to trace the evolution of the flare plasma from an adaptively smoothed X-ray median energy of flare counts, and standard solar flare models to derive sizes of flaring coronal structures. We classify COUP flares into several morphological groups including "typical" rapid-rise-slow-decay and "slow-rise-and/or-top-flat" (SRTF). Rise and decay times range from hours to >1day, peak luminosities span $10^{30.5}$-$10^{32.9}$ erg/s range, and peak plasma temperatures - ~20 - >100 MK. For 80% of the flares, inferred coronal loop sizes span 0.5-6R_{star} while the remainder have even larger loops. We provide an electronic atlas of this unique collection of stellar X-ray flares. Two main results are obtained. First, we find evidence that the coronal extent of PMS stars with inner circumstellar disks does not exceed the Keplerian corotation radius. In contrast, ~30% of stars without inner disks have coronas extending up to two corotation radii. This supports the model of Jardine et al. (2006) for coronal stripping by circumstellar disks. However, there is no relationship found between flare morphology and an inner disk indicative that star-disk field lines produce distinctive flare types. Second, our analyses indicate that the rapidly accreting PMS stars lack long-lasting and morphologically complex flare events such as SRTFs, events which could involve multiple flares from the entire coronal magnetosphere. We speculate that the progression of magnetic reconnection in multipolar magnetospheres ceases when it reaches an accretion hotspot with mass loaded coronal loops.

Aim: The 13 day COUP observation provides a unique opportunity to study relatively rare long-lasting flare events from PMS (pre-main sequence) stars. The classical method of time sliced spectroscopy permitted Favata et al. (2005) to analyze the brightest ~1% of the COUP flares (32 flares). Many of these flares were found to be associated with very long magnetic structures (L>>R*). Such structures were predicted by magnetospheric models but never identified observationally before. However, 32 flares did not provide sufficient statistics (in terms on number of flares) to allow for a formal analysis of whether such long coronal structures are linked to the presence of disk and/or high accretion signatures. The aim of the present study is to increase the flare sample by utilizing an innovative method of flare analysis, and to provide new observational information regarding the relationship between long coronal structures, circumstellar disks and accretion in PMS stars.

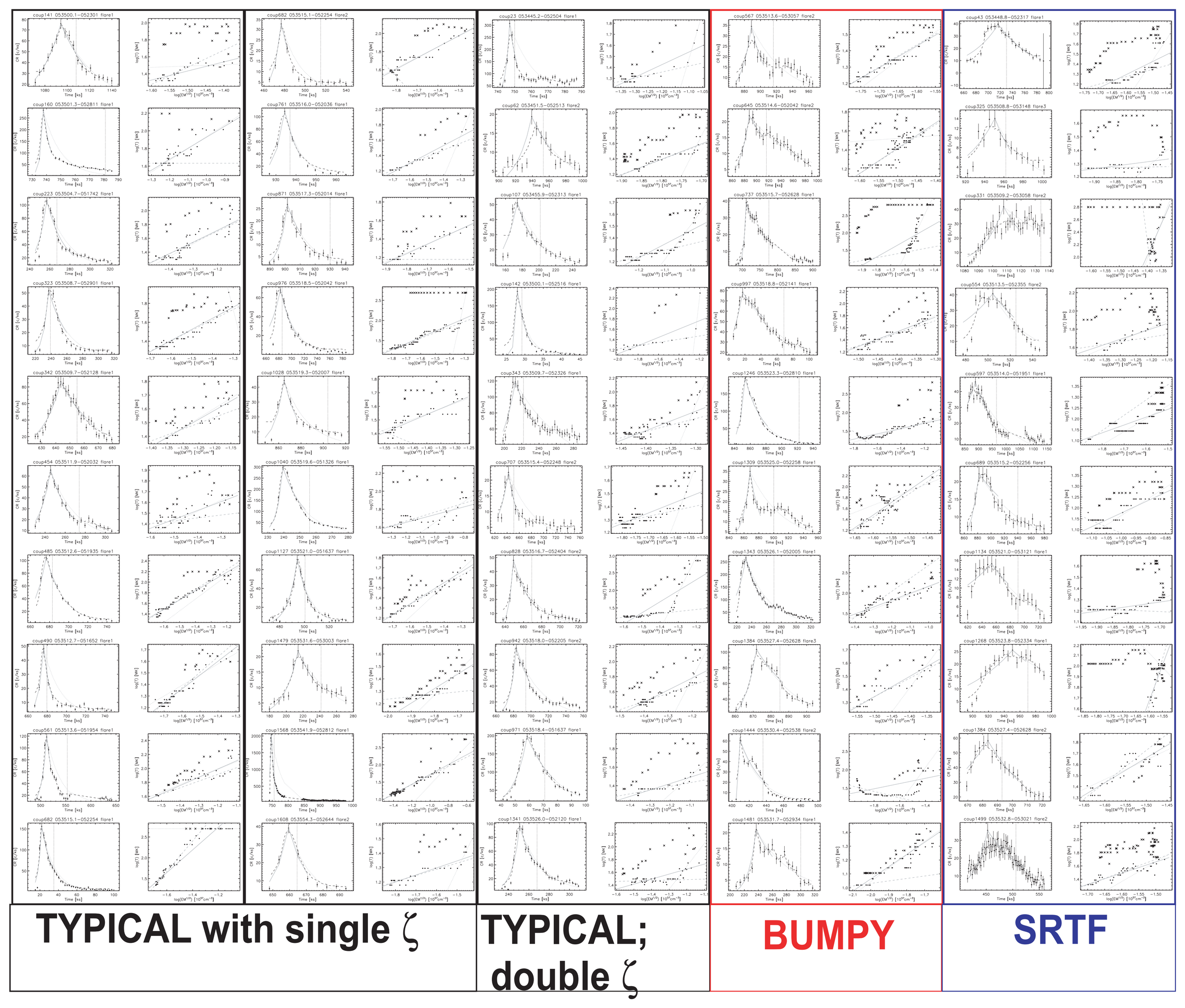


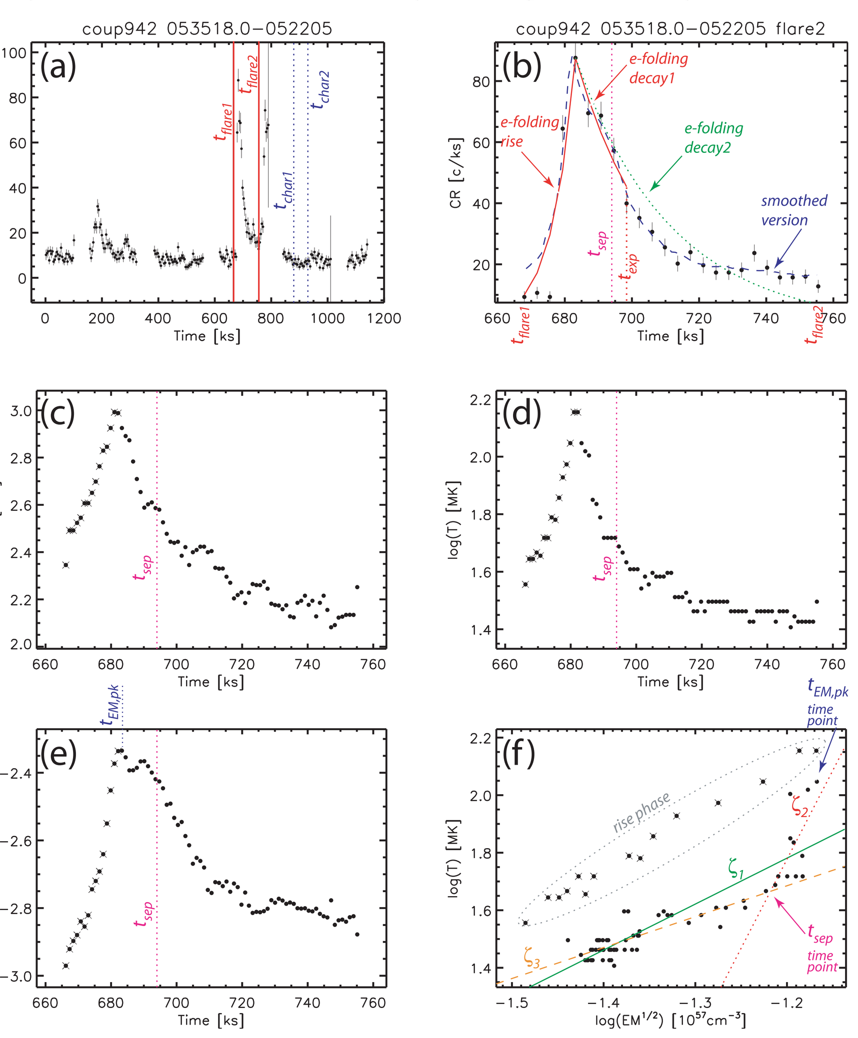
Method: With detailed data on the decay of flux and temperature during the cooling flare phase, we can infer properties of the radiating plasma structure within the framework of the time-dependent hydrodynamic model in a SINGLE coronal magnetic loop. With the proper account for prolonged heating during the decay phase Reale et al. (1997) find $L = \alpha \times \tau_d \times (T_{pk})^{1/2} / F(\zeta)$, where L - loop size, α - numerical constant, τ_d - flare decay time, T_{pk} - peak plasma temperature, $F(\zeta)$ - correction for prolonged heating as a function of slope ζ of the trajectory in the temperature-density diagram.

Method: Instead of performing time-sliced spectroscopy with XSPEC over a few characteristic time blocks of the lightcurve, we employ an adaptively smoothed median energy time series to derive dozens of time points of (kT,EM) along the decay phase of the lightcurve. This is achieved by calibrating median energies to temperatures using the spectral simulations described in Getman et al. (2006). Median energies are more statistically stable for small-N datasets than kT parameters of nonlinear XSPEC regressions. We assume source column density (N_H) is constant and we take it from the spectral global fits of COUP sources (Getman et al. 2005); and we ignore the weak soft spectral component that is likely present from the quiescent (characteristic) background. Calibration results for a few representative source column densities are exemplified in the figure ->.



Method: In order to obtain optimal results within the framework of the Reale et al. 1997 simple single compact loop model it is suggested that the lightcurve should not present significant deviations from a pure exponential decay and that the decay trajectory in the density-temperature plane has to be linear. Strong morphological deviations from an exponential decay and/or absence of a single linear trajectory could be indications of more complex events, such as multiple coronal loops (e.g. a loop arcade similar to a 2-ribbon solar flare) and/or complex heating (see Reale et al. 2004, 2007). However, even in the case of a complex flare it is possible to apply a single loop model approach to a lightcurve segment if there is an indication for the presence of a single DOMINANT loop. Based on the analysis of the August 2001 flare with the "bumpy" decay from Proxima Centauri, Reale et al. (2007) argues that when multiple loop structures are involved in the flare, the rise and early decay are often dominated by a single primary loop.

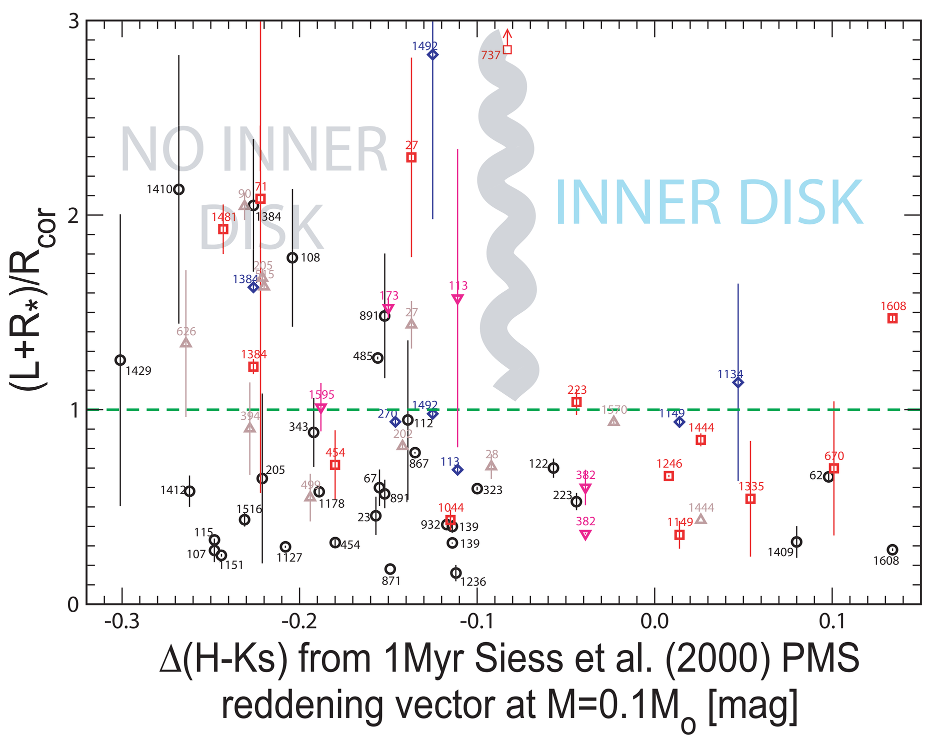




Method: COUP flares are morphologically classified into several groups with the four basic distinctive and likely physically meaningful groups listed in order of their complexity: 84 **typical**, 38 **bumpy**, 8 **double**, and 20 slow-rise-and/or-top-flat (**srf**). Lightcurves along with inferred temperature-density trajectories for some representative flares are shown in the figure above. Two other mutually overlapped groups, **incomplete** and **other**, are likely derivatives from the four above, with their lightcurves either severely interrupted by the COUP observational gaps and/or poorly defined, generally due to their lower counting statistics. In the assumption of the presence of a dominant structure we derive loop size ranges for most of the COUP flares (using ranges of inferred e-folding timescales [τ_{d1}-τ_{d2}] and a preferably dominant slope ζ if applicable), bearing in mind that the inferred sizes are likely less reliable for the morphologically complex types such as double and SRTF flares.

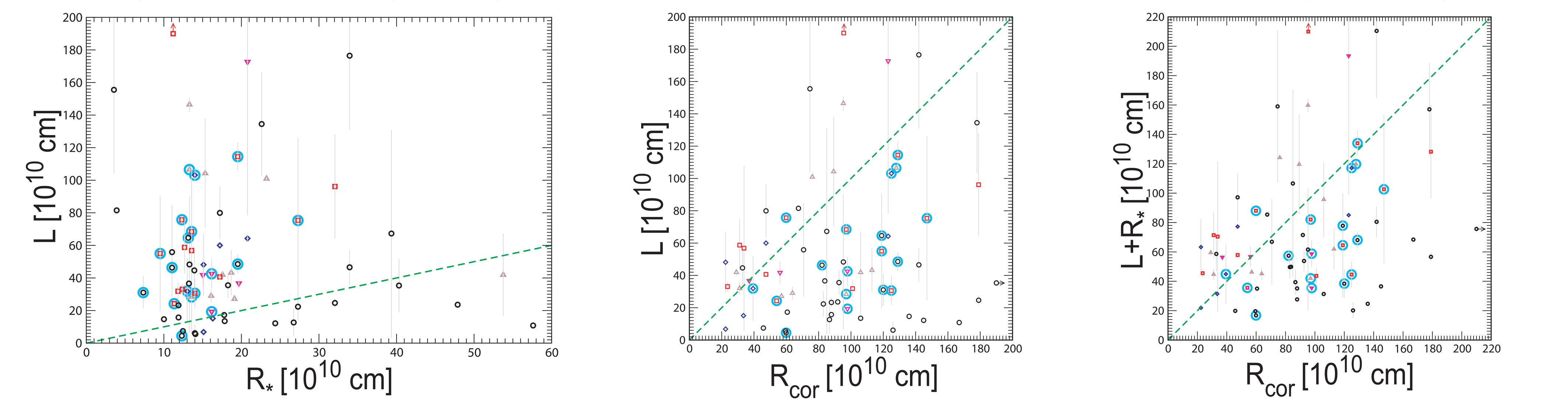
Method: We provide the catalog and the electronic atlas of these unique flares. <-Sample page from the atlas shows the X-ray spectral modelling of the exemplifying flare #2 of the COUP source #942 using the method of the adaptively smoothed median energy.

Flares shown on all graphs below are color-coded as follows: **typical** - black circles, **bumpy** - red boxes, **double** - green Xs, **SRTF** - blue diamonds, **incomplete** - brown triangles, **other** - magenta triangles, and flares from **Ks-disky** stars are outlined by cyan circles.



Results: **Coronae and Disks.** For 69 flares from 56 COUP sources with known stellar masses (*M*), radii (*R*), rotation periods (*P*), and inner disk indicators established from JHKs-band photometry (Δ(H-Ks)), we plot the ranges of the inferred lengthes of their coronal flaring structures scaled to their Keplerian corotation radii ($R_{cor} = (GMP^2/4\pi^2)^{1/3}$). The plot provides an indication that PMS stars with inner disks preferentially have flaring coronal structures with sizes <= Rcor, while some of the PMS stars without Ks-band inner disks possess structures 1.5-2 Rcor long. This observational finding is in accord with the simple model of the coronal extent in T-Tauri stars proposed by Jardine et al. (2006): the coronae of T-Tauri stars may extend outward until either the pressure of the hot coronal gas overcomes the magnetic field, or, if the corona interacts with a disk before this happens. In this model with the consideration of typical emission measures observed in COUP stars and with the assumption of a simple dipolar magnetic field geometry, coronal extents for low-mass stars indeed are expected to reach1.5-2 Rcor. The centrifugal striping of the coronal outer parts proposed for rapidly rotating main-sequence stars (e.g. Jardine 2004) is not considered important for relatively slow rotatingT-Tauri stars.

Results: The quantity of the coronal extent in units of the Keplerian corotation radius shown above is composed of the three independent variables (*R*, *Rcor*, and *L*); and the inferred coronal loop size variable (*L*) indeed contributes a significant weight to this quantity, as it is shown in the three figures below with the Ks-band disky stars outlined by cyan circles. The deficit of the very low-mass stars (thus low *Rcor* at typical rotational periods of 5-10 days) with Ks-band inner disks may present some observational bias to our findings, and thus even larger flaring source sample with known stellar characteristics is desired to verify the findings.



Results: **Accretion and SRTFs**. Among a few known disk indicators from the COUP database (Getman et al. 2005) the Δ(H-Ks) is the one that best correlates with the accretion indicator EW(CaII) (Figure A). The inferred coronal extents for the accreting stars (a subclass of disky stars) is found also not to exceed Rcor (graph is not shown).

Among the COUP PMS flare morphological classes the class of SRTF flares is the most intriguing and unusual one (in regards to solar analogous). Grosso et al. (2004) observed an SRTF flare from the low-mass PMS star with a weak NIR excess, LkHa312 in M78. Within the framework of solar physics they derived the magnetic loop height for the flare to be only 0.2-0.5R*. However, they had difficulty to explain the true origin of such flare. The most plausible explanations included enhanced microflaring processes (in regards to the Sun) and/or a volume filling factor 1000 times larger than in solar corona. In the present study we provide additional observational support for such explanations: 1. SRTF flares are seen on both, COUP disky and non-disky stars, with no preference (blue diamonds on Figure A), thus likely are not related to the presence of disks; 2. SRTF is the only class of COUP flares for which flare duration correlates with global stellar properties, possibly mass and/or radius (see Figure B); 3. SRTF flares as well as other long lasting events are NOT observed in highly accreting COUP stars (see Figure C). These findings lead us to speculate that SRTFs may represent the enhanced versions of 2-ribbon solar flares, sets of sequentially reconnecting magnetic coronal structures, but residing in the much larger surface areas whose sizes are comparable to the entire stellar magnetosphere.