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X-RAY PHOTOEVAPORATION-STARVED T TAURI ACCRETION

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ABSTRACT

X-ray luminosities of accreting T Tauri stars are observed to be systematically lower than those of nonaccretors. There is as yet no widely accepted physical explanation for this effect, though it has been suggested that accretion somehow suppresses, disrupts or obscures coronal X-ray activity. Here, we suggest that the opposite might be the case: coronal X-rays modulate the accretion flow. We re-examine the X-ray luminosities of T Tauri stars in the Orion Nebula Cluster and find that not only are accreting stars systematically fainter, but that there is a correlation between mass accretion rate and stellar X-ray luminosity. We use the X-ray heated accretion disk models of Ercolano et al. to show that protoplanetary disk photoevaporative mass-loss rates are strongly dependent on stellar X-ray luminosity and sufficiently high to be competitive with accretion rates. X-ray disk heating appears to offer a viable mechanism for modulating the gas accretion flow and could be at least partially responsible for the observed correlation between accretion rates and X-ray luminosities of T Tauri stars.

Key words: planetary systems: protoplanetary disks – stars: coronae – stars: formation – stars: pre-main sequence – stars: winds, outflows – X-rays: stars

1. INTRODUCTION

A survey of the X-ray emission from T Tauri stars in the Taurus-Auriga star-forming region by Neuhaeuser et al. (1995) based on *ROSAT* observations revealed a significant difference amounting to a factor of 2–3 between the X-ray luminosities of classical T Tauri stars (CTTS) still in the phase of active accretion, and weak T Tauri stars (WTTS) of the same mass that exhibit no accretion signatures. This finding was confirmed in subsequent *ROSAT* studies of Taurus-Auriga and other nearby star-forming regions (e.g., Alcala et al. 1997; Wichmann et al. 1997; Stelzer & Neuhäuser 2001; Flaccomio et al. 2003a), in later *XMM-Newton* surveys of the Taurus molecular cloud (Telleschi et al. 2007) and NGC 2264 (Dahm et al. 2007), and by *Chandra* X-ray surveys of low-mass stars in the Orion Nebula Cluster (ONC) (Flaccomio et al. 2003b; Stassun et al. 2004; Preibisch et al. 2005), and NGC 2264 (Flaccomio et al. 2006). This general result might be considered surprising since the additional energy input through accretion might naively be expected to result in *additional* X-ray emission through ballistic accretion shocks rather than in diminished X-rays (e.g., Lamzin et al. 1996; Lamzin 1999; Calvet & Gullbring 1998).

Several different explanations for the X-ray deficiency of accreting T Tauri stars have been proposed (e.g., Flaccomio et al. 2003b; Stassun et al. 2004; Preibisch et al. 2005; Jardine et al. 2006; Güdel et al. 2007; Gregory et al. 2007), including disruption of the magnetic corona by the encroaching accretion disk, suppression of convection through the influence of accreted gas on stellar structure, reduction in differential rotation due to star-disk interactions, and obscuration of X-ray emission by accretion funnels. All of these explanations involve the suppression of X-rays as a consequence of accretion. We suggest here that, instead of accretion modulating X-ray emission, X-ray emission itself might be a driver modulating the accretion.

Recent results of two-dimensional photoionization and radiative transfer calculations of the heating of protoplanetary disks by parent stellar coronal X-rays by Ercolano et al. (2008a) indicate that the X-rays drive a disk coronal wind of significant mass flux. The estimated mass-loss rate for a 0.75 $M_\odot$ star with a rather typical ONC X-ray luminosity of 2×10^{30} erg s^{-1} was of order 10^{-8} $M_\odot$ yr^{-1}. Moreover, the mass loss was dominated by the region of the disk lying at a radial distance of 10–20 AU. In principle, such a photoevaporation zone could drive off a significant fraction of the migrating gas from the outer disk and starve the inner disk of gas to replenish the accretion flow onto the star. The photoevaporation rate, and the extent to which inflowing gas is driven off the disk, should be correlated with the stellar X-ray luminosity.

Here, we present new evidence that not only are the accretors less X-ray luminous than nonaccretors, but that the mass accretion rates of ONC CTTS are inversely correlated with X-ray luminosity, as also suggested recently for Taurus molecular cloud stars by Telleschi et al. (2007). We propose that this could be a signature of X-ray photoevaporation-starved accretion flow; stars that are more X-ray bright are naturally accreting at lower rates because the supply of gas to the inner disk is diminished by photoevaporative dissipation. In Section 2, we outline extensions to the disk model calculations of Ercolano et al. (2008a) to investigate the influence of X-ray luminosity on photoevaporation rate, and in Section 3 we present a fresh analysis of the Ca II 8662 Å accretion diagnostic and stellar X-ray luminosities for stars of the ONC observed in the *Chandra* Orion Ultra-Deep survey (COUP; Feigelson et al. 2005). The results are discussed and summarized in Sections 4 and 5.

2. X-RAY PHOTOEVAPORATION OF DISK GAS

Ercolano et al. (2008a) have recently presented an estimate of the photoevaporation rate of gas in a protoplanetary disk driven by X-ray heating. In order to gain further understanding of the dependence of the mass-loss rate on X-ray luminosity, we have performed photoevaporation rate calculations for identical disk parameters used by Ercolano et al. (2008a), but for different values of the stellar X-ray luminosity.

The basis of our X-ray photoevaporation estimate is a two-dimensional photoionization and dust radiative transfer model calculated using the MOCASSIN Monte Carlo code (Ercolano et al. 2003, 2005, 2008b) of a prototypical T Tauri disk irradiated by X-rays. The model of Ercolano et al. (2008a) assumed a 0.1–10 keV luminosity for the central pre-main-sequence star of $L_X = 2 \times 10^{30}$ erg s^{-1}; here we performed analogous calculations for values of X-ray luminosity ranging from 2×10^{29} to 4×10^{31} erg s^{-1}, bracketing the value adopted by Ercolano et al. (2008a) by factors of 10. The X-ray source was assumed to be an optically thin, collision-dominated plasma with a temperature of $\log T = 7.2$. The disk was assumed to have the initial dust and gas density distribution of a two-dimensional disk model computed by D'Alessio et al. (1998) for a central star of mass 0.7 $M_\odot$, radius 2.5 R$_\odot$, and effective temperature 4000 K, and for an accretion rate $\dot{M} = 10^{-8} M_\odot$ yr^{-1}, viscosity parameter $\alpha = 0.01$ (see, e.g., Pringle 1981), and total disk mass 0.027 $M_\odot$. In a refinement over the method used by Ercolano et al. (2008a), the vertical gas density structure was additionally iterated from the starting solution to preserve hydrostatic equilibrium (HSE) using a version of the formalism of Alexander et al. (2004), modified to account for significant vertical extension of the disk gas. A more complete description of the model calculations is presented by Ercolano et al. (2009).

Following Alexander et al. (2004) and Ercolano et al. (2008a), the photoevaporation rate through X-ray heating at each radial grid point, R, was estimated by assuming the base of the flow is located at the height where the local gas temperature exceeds the escape temperature of the gas, defined as $T_{es} = G m_H M_* / kR$, where M_* is the stellar mass. To a first approximation, the mass-loss rate per unit area is ρc_s, where ρ and c_s are the gas density and the sound speed evaluated at the base of the flow, respectively.

The total disk mass-loss rate as a function of stellar X-ray luminosity is illustrated in Figure 1, and the mass-loss rate integrated over an annulus of unit width as a function of the annular radius, R, is illustrated for models corresponding to different stellar X-ray luminosities in Figure 2. As noted by Ercolano et al. (2008a), the mass-loss rate peaks strongly in the 10–20 AU range—a zone far enough from the central star that escape temperatures are sufficiently low for the decreasing X-ray heating with increasing radius to affect the maximum mass loss. The mass-loss rate is found to depend strongly on stellar X-ray luminosity, as expected.

The photoevaporation rate for the canonical model with $L_X = 2 \times 10^{30}$ erg s^{-1} is about a factor of 10 lower than the non-HSE, fixed density structure calculation of Ercolano et al. (2008a): this is due to the screening capacity of the vertical evaporated gas flow that acts to partially shield the disk from X-rays. The HSE calculations here will in fact overestimate this screening because the true gas density in outflowing unbound gas will be lower than that for the HSE solution in which the gas pressure has to support the overlying column. The HSE photoevaporation rate will then underestimate the true photoevaporation rate. Nevertheless, within the bounds of accuracy of the calculations, we find X-ray photoevaporation rates comparable with observed accretion rates of CTTS. We also find a strong dependence of photoevaporation rate on L_X: for a factor of 100 change in L_X the disk mass-loss rate changes by a factor of ∼50.

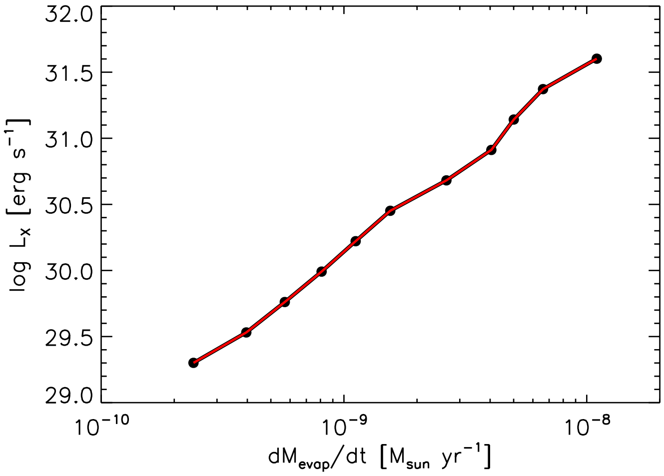

Figure 1. X-ray heating-induced photoevaporation rate, $\dot{M}$, from a 2D protoplanetary disk model expressed as a function of the model coronal X-ray luminosity of the central star, L_X, computed using the MOCASSIN program (see the text and Ercolano et al. 2008a for details).

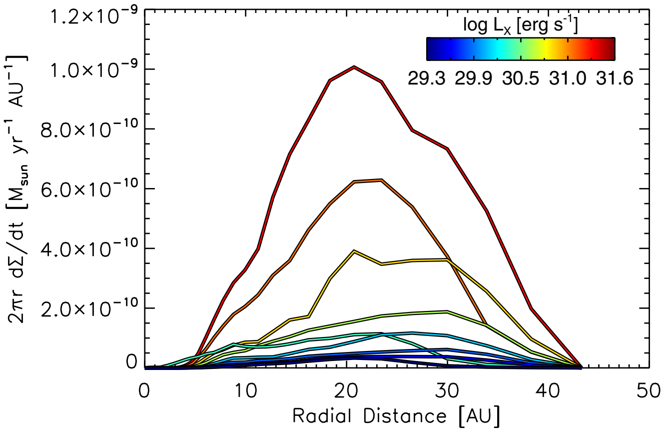

Figure 2. Photoevaporation rate per unit radius, $d\Sigma/dt$, as a function of radial distance from the central star for different stellar X-ray luminosities, L_X. The evaporation rate peaks in the region 20 AU and at high values of L_X can compete with the inward viscous flow, starving the inner disk of the replenishing gas from the outer disk that contains the bulk (∼90%) of the total disk gas mass.

3. Ca II AND AN L_X–$\dot{M}$ RELATIONSHIP FOR THE ONC

Strong blue and near-infrared lines of Ca II are formed purely in absorption in nearly all late-type stellar photospheres, with some sensitivity to stellar effective temperature and metallicity (e.g., Smith & Drake 1987, 1990; Chmielewski 2000). In magnetically active stars, the lines are observed to be filled in by emission from the chromosphere. In the case of accreting T Tauri stars, the photospheric line in-filling is thought to be caused also by emission from regions of the upper atmosphere heated by magnetospheric accretion. This occurs to such an extent that the lines can be seen in emission, and the emission line strength of the infrared Ca II lines has been found an excellent diagnostic of mass accretion rate, $\dot{M}$, (e.g., Batalha et al. 1996; Muzerolle et al. 1998).

Flaccomio et al. (2003b) used the Ca II 8662 Å equivalent width measurements of Hillenbrand et al. (1998) to divide their *Chandra* sample of X-ray detected T Tauri stars in the ONC into "high" and "low" accretion rates, and then to find differences in the X-ray luminosity functions of these two groups (see also Stassun et al. 2004; Preibisch et al. 2005). Here, we revisit the Hillenbrand et al. (1998) Ca II 8662 Å equivalent width data with a view to making a more precise assessment of the mass accretion rates of ONC stars for which both Ca II and X-ray luminosity measurements exist.

The relationship between the observed Ca II 8662 Å flux, F_{CaII}, and mass accretion rate, $\dot{M}$, has been studied in detail

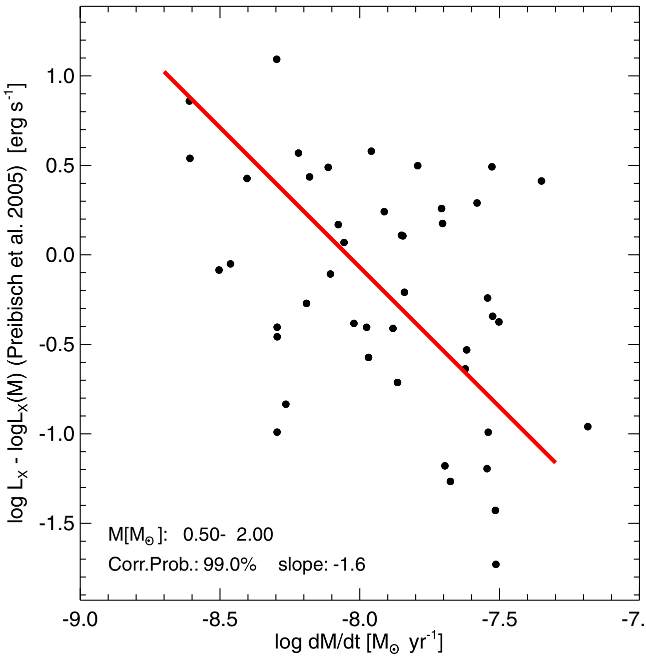

Figure 3. Deviation of ONC T Tauri X-ray luminosity from the mean L_x vs. stellar mass, M, relation of Preibisch et al. (2005) as a function of derived mass accretion rate (see the text). The Spearman's ρ correlation probability is 99%. The correlation indicates that, on average, stars with higher X-ray luminosity have lower mass accretion rate, $\dot{M}$.

by Mohanty et al. (2005) for a wide range of stellar mass. For CTTS, they find (their Equation (2))

$$\dot{M} = 0.71 \log_{10}(F_{CaII}) - 12.66. \tag{1}$$

We adopt this relationship as the basis of our $\dot{M}$ calibration for the ONC sample, together with the compilation of relevant data from Getman et al. (2005). The latter includes X-ray luminosities from the COUP survey, Ca II equivalent widths from Hillenbrand et al. (1998), stellar effective temperatures and bolometric luminosities updated from Hillenbrand (1997), and stellar masses inferred from the evolutionary tracks of Siess et al. (2000).

Since Equation (1) involves the *flux* of the Ca II 8662 Å line, rather than the equivalent width, we have converted the latter measurements of Hillenbrand et al. (1998) into fluxes using the predicted continuum fluxes of the model atmospheres of Allard et al. (2000). These models span an effective temperature range of 3000–5000 K, and the logarithmic surface gravity range 3.5–5.5. The 8662 Å continuum intensity for each star was obtained by interpolation in the model grid for the appropriate values of effective temperature and surface gravity. We derived the latter from the masses, temperatures, and luminosities tabulated by Getman et al. (2005). Out of 502 stars with spectral types, effective temperatures and Ca II equivalent width measurements, we obtained $\dot{M}$ estimates for 412. We further restricted the sample range to stars with mass 0.5 $M_\odot < M < 2.0$ $M_\odot$: being intrinsically more faint, stars of lower mass are prone to larger uncertainties in observed X-ray fluxes and samples are inherently less complete; higher-mass stars have essentially radiative envelopes and likely exhibit quite different X-ray and disk behavior. The stars of this sample with X-ray luminosity measurements numbered 120, and of these 45 have mass accretion rates $\dot{M} > 0$; the remainder have Ca II 8662 Å either in absorption or with an equivalent width of zero.

Since the final sample of 45 stars covers a significant mass range, and pre-main-sequence stellar X-ray luminosity depends on stellar mass, we studied the L_X–$\dot{M}$ relationship by comparing our derived mass accretion rates with *deviations* from the mean L_X versus M relation derived for the COUP sample by Preibisch et al. (2005), $\Delta \log L_X = \log L_X - \log L_X(M)$. This is illustrated in Figure 3, where we find evidence for an *inverse* correlation between $\dot{M}$ and $\Delta \log L_X$: the Spearman's ρ correlation probability is 99% and the best-fit slope is -1.6. Similar anticorrelations are seen in L_X/L_{bol} versus $\dot{M}$ (correlation probability 99.94%, slope $= -1.9$) and in L_X/L_{bol} versus $\dot{M}/M$ (correlation probability 99.96%, slope $= -1.6$). These data provide strong evidence that stars of a given mass with higher X-ray luminosity have lower mass accretion rates: the initial finding of Neuhaeuser et al. (1995) that WTTS are generally more X-ray bright than CTTS appears to be the manifestation of a continuous relation between X-ray luminosity and accretion rate.

4. DISCUSSION

In Section 1, it was noted that current ideas attempting to explain the lower X-ray luminosities of accreting T Tauri stars all seek to exploit possible suppression or disruption of coronal activity by accretion. Since the X-ray photoevaporation rates we find in Section 2 are of a similar order of magnitude to mass accretion rates, we suggest here that accretion can instead be modulated by coronal X-ray luminosity. We find that the bulk of the disk mass loss occurs at a radial distance of 20 AU, and it is this evaporative flow that can "starve" the viscous flow of gas to the inner disk. A recent disk photoevaporation study by Gorti & Hollenbach (2009) also finds the 10–20 AU region to dominate the photoevaporative flow, with mass-loss rates similar to those from our study (though in their model the flow is primarily driven by FUV heating; we defer a more complete discussion of the model differences to future work). Were all inward gas flow to be curtailed at a radial distance of 10–20 AU, the disk inward of this point would essentially be cleared of gas on the viscous timescale. For our canonical disk model, taken from D'Alessio et al. (1998), the inner 10 AU contains only a few percent of the total disk mass and the clearing time is of order 10^5 yr.

The inner disk clearing time also represents the timescale for which a given star must have a relatively high X-ray luminosity for the accretion flow to become completely starved of gas by photoevaporation. While it is possible that shorter periods of high X-ray luminosity could give rise to depleted radial "stripes" that are manifest in a lower accretion rate on reaching the very inner disk, the correlation between the two properties L_X and $\dot{M}$ could in such a case be erased during any given snapshot in time.

The inner disk clearing time is important in the context of the large range of observed X-ray luminosities of T Tauri stars. Preibisch et al. (2005) noted the very large scatter of observed X-ray luminosity in relation to other stellar parameters, such as stellar mass. In that case average deviations amount to ±0.7 dex from the mean relation. In order for photoevaporation to be at least partially responsible for the observed correlation between accretion rate and X-ray luminosity, the scatter in the latter must be due mostly to long-term intrinsic differences rather than short-term variability. Preibisch et al. (2005) ruled out stellar flaring and short-term stochastic variability as being responsible for the L_X scatter, largely by comparison of COUP observations with shorter *Chandra* ACIS ONC observations obtained several years earlier which indicated a median deviation of only a factor of ∼2. We confirm this conclusion by comparison of stellar L_X values from COUP with those from the *Chandra* HRC ONC survey of Flaccomio et al. (2003b): when sources of scatter due to different analysis procedures and different instrumental bandpasses are accounted for, the deviation from parity between the surveys only amounts to about a factor of 2. Nevertheless, the L_X scatter among T Tauri stars represents a possible test of the relative importance of X-ray photoevaporation: should future studies, perhaps over longer time baselines, find the scatter to be caused by relatively short-term changes (activity cycles perhaps, that have not yet been seen in T Tauri stars), then photoevaporation-starved accretion could not give rise to the observed L_X–$\dot{M}$ correlation.

Finally, while it is suggested here that X-ray photoevaporation can drive the correlation between X-ray luminosity L_X and mass accretion rate, and consequently the X-ray luminosity differences between CTTS and WTTS, the true explanation might involve more than one mechanism, and it is possible that both coronal disruption and photoevaporation play a role.

5. SUMMARY

New calculations of T Tauri disk photoevaporation due to stellar X-radiation find mass-loss rates highly correlated with X-ray luminosity and of a similar magnitude to mass accretion rates. The results lead us to suggest that irradiation of protoplanetary disks by stellar X-radiation can starve the accretion flow onto the central star through photoevaporation. Such a process could explain the higher average X-ray luminosities of nonaccreting T Tauri stars compared with those of accretors. We find from an analysis of the Ca ii 8662 Å accretion diagnostic for T Tauri stars in Orion that the mass accretion rate is also correlated with stellar X-ray luminosity, as expected in the photoevaporation-starved accretion scenario.

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