THE ASTROPHYSICAL JOURNAL, 446:341–349, 1995 June 10


# *EINSTEIN* OBSERVATIONS OF T TAURI STARS IN TAURUS-AURIGA. II. RELATIONSHIPS BETWEEN X-RAY EMISSION AND PRE–MAIN-SEQUENCE ACTIVITY

F. DAMIANI AND G. MICELA
Istituto ed Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, 90134 Palermo, Italy;
fdamiani, gmicela@oapa.astropa.unipa.it
*Received 1993 June 15; accepted 1994 December 14*

## ABSTRACT

On the basis of the full set of reanalyzed *Einstein* IPC X-ray data on Taurus-Auriga pre–main-sequence stars, presented in a companion paper, we have studied the relationships between the X-ray emission and typical diagnostics of pre–main-sequence activity to obtain indications of the origin of the X-ray emission and of the structure of the outer atmospheres in these stars. We argue that, in the case of classical T Tauri stars, scaling the Hα luminosity to the infrared (disk) emission is much more meaningful physically than scaling it to the stellar continuum (by considering the line equivalent width). We find an inverse relation between the X-ray luminosity and this infrared-scaled Hα emission. We also find an anticorrelation between X-ray luminosity and rotational period, in qualitative agreement with earlier works; this is interpreted in terms of a magnetic origin for the X-ray emission. This relationship, however, is limited to stars younger than $2 \times 10^6$ yr, while for the older sample stars, saturation of X-ray surface flux appears to take place. We interpret the relation found between X-ray and infrared-scaled Hα emission as a competition between closed and open magnetic structures on the surface of these stars. In the stars without indications of winds and accretion disks (weak-line T Tauri stars), a correlation between X-ray luminosity and unscaled Hα luminosity is found instead, providing further evidence for the chromospheric origin of the line emission in these latter stars.

*Subject headings:* stars: activity — stars: pre–main-sequence — X-rays: stars

## 1. INTRODUCTION

We have presented in a companion paper (Damiani et al. 1995, hereafter Paper I) a systematic reanalysis of *Einstein* X-ray data on the pre–main-sequence (PMS) population in the Taurus-Auriga complex; there we have discussed the average properties of the X-ray emission of these stars, together with a consideration of the statistical significance of the various results. By considering the subsamples of strong and weak emission line stars, we found a difference between their X-ray luminosity distributions. Here we use the same sample to look more closely for relationships between X-ray emission and emission-line activity typical of PMS stars; at the same time, we discuss the relationship with stellar rotation, which gives indications on the origin and evolution of the X-ray emission of T Tauri stars.

Relationships between X-ray emission from these stars and their line emission have been studied by Walter & Kuhi (1981) for a sample of classical T Tauri stars (CTTSs) in Taurus-Auriga; they claim that an anticorrelation exists between the line equivalent width and the X-ray luminosity in their sample and propose an interpretation for it in terms of selective absorption of X-rays in the stars with the strongest emission-line activity. Other studies by Feigelson & Kriss (1989) on the Chamaeleon star-forming region, however, failed to confirm this anticorrelation.

A correlation between X-ray activity level (specifically, X-ray surface flux) and stellar rotation rate has been reported by Bouvier (1990). However, it is still worthwhile to reconsider these correlations, since Bouvier (1990) generally uses X-ray data coming from the early (REV 0) release of *Einstein* data from a variety of sources in the literature and therefore lacking the homogeneity of reduction characterizing our survey (Paper I). Indeed, a detailed comparison between REV 0 and REV 1 data (cf. § 2.2 of Paper I) reveals that in a fraction of cases REV 1 changes significantly the deduced source rates.

In § 2 we present what (we believe) are the essential features of a realistic picture of the circumstellar environment of T Tauri stars, in terms of which we will interpret our results. Section 3 is a presentation of the observed relations of X-ray emission with rotation and line emission, and the resulting picture for PMS stars is discussed in § 4. Section 5 is a summary of the main results obtained.

## 2. MODEL FRAMEWORK

### 2.1. *The Most "Fundamental" Indicator of Activity in T Tauri Stars*

T Tauri stars are well known to have continuum emission excesses at near-IR and UV wavelengths (Rydgren & Vrba 1981, 1983; Herbig & Goodrich 1986). Also, the *IRAS* satellite detected a large number of T Tauri stars as strong far-IR sources, in four bands at nominal wavelengths of 12, 25, 60, and 100 μm. The total luminosity of each IR source in these bands turns out to be often of the same order of magnitude as the optical luminosity of the associated T Tauri star, and in some cases even larger (Harris, Clegg, & Hughes 1988; Strom et al. 1988; Cabrit et al. 1990; Beckwith et al. 1990). A variety of arguments, ranging from the broad spectral energy distribution in the IR to the relatively clear line of sight toward the stellar photospheres ($A_V \sim 1$–2 mag), have led to the interpretation of the IR emission as arising in circumstellar disks (Adams, Lada, & Shu 1987; Bertout, Basri, & Bouvier 1988; Beckwith et al. 1990).

Infrared luminosities larger than stellar luminosities, together with UV excess emission thought to arise from boundary layers between the star and disk, indicate unambiguously that accretion really takes place, at least for the more active stars.

High spectral resolution observations have clearly shown that the profiles of the strong emission lines are generally broad, often with a complex structure, suggesting macroscopic mass motions in the outer atmospheres/circumstellar environment of these stars (e.g., Hartmann 1982; Mundt 1984). In fact, wind models succeeded in reproducing both the observed line intensities and the profiles (e.g., Hartmann, Edwards, & Avrett 1982; Hartmann et al. 1990), which deep-chromosphere models failed to explain (Calvet, Basri, & Kuhi 1984). Instead, enhanced-chromosphere models seem appropriate to reproduce emission lines in weak-line T Tauri stars (WTTSs), as also suggested by the narrow and regular line profiles of these latter stars.

Cabrit et al. (1990) find that the (Balmer and forbidden) line luminosity, in a sample composed essentially of CTTSs, is well correlated with the IR luminosity; they suggest a possible interpretation of this result as an indication of the observed winds being driven by the accretion process. In this respect it has been noticed that strong line emission, with structured line profiles, disappears precisely in those stars lacking detectable far-IR emission (Walter et al. 1988; Strom et al. 1989) and that the mass-loss and mass accretion rates as derived from the most recent models are of the same order of magnitude (Cabrit et al. 1990, and references therein), the models being too rough at present to allow a search for tighter relations.

From this picture it is evident that the line emission has to be regarded as a final product of a series of processes, ultimately caused by the accretion of matter from a circumstellar disk, and is therefore a quite indirect diagnostic of this accretion activity. A much more direct way to look at the source of activity, therefore, is to study the disk emission at infrared wavelengths directly (Adams et al. 1987). Between 25 and 60 $\mu$m the disk emission prevails over any purely stellar or interstellar emission component, and observations at these wavelengths should provide the most direct information about accretion activity. On this basis we prefer to rely on the IR emission as a fundamental indicator of accretion activity (and general PMS activity as well), rather than to adopt indirect diagnostics such as the line luminosities, whose generation mechanism is surely less clear.

For these reasons, in the following we will often consider separately stars above and below the *IRAS* detection threshold (of $\sim$0.1 Jy) at 25 $\mu$m as two classes of physically different objects. Henceforth, we will call "classical" (CTTSs) and "weak-line" T Tauri stars (WTTSs), respectively, stars detected and undetected by *IRAS* at 25 $\mu$m, rather than follow the more common usage of regrouping stars according to their H$\alpha$ equivalent width.

## 3. RELATIONSHIPS OF X-RAY EMISSION WITH OTHER STELLAR PROPERTIES

### 3.1. *Stellar Rotation*

For slowly rotating main-sequence and giant stars, well-defined relations are known to exist between rotation and X-ray emission (Pallavicini et al. 1981; Maggio et al. 1987) or chromospheric emission (Noyes et al. 1984) and are usually taken as indicative of emission mechanisms related to the magnetic field. The relation which late-type stars in general are found to obey is of the kind $L_x \propto (v \sin i)^2$, independent of luminosity class (Pallavicini et al. 1981), although important exceptions are the Pleiades fast rotators ($v \sin i > 30$) (Caillault & Helfand 1985; Micela et al. 1990), or the high X-ray luminosity, fast-rotating stars in the Extended Medium Sensitivity Survey (Fleming, Gioia, & Maccacaro 1989) and in the *Einstein* Slew Survey (Schachter et al. 1995).

In order to study the extent to which such relations hold for our T Tauri star sample, we have searched the published literature for rotational periods ($P_{rot}$) for the sample stars, as reported in Table 1 of Paper I. The use of periods deduced from periodic photometric light curves is preferable to $v \sin i$, since it is unaffected by both projection effects and uncertain spectral type assignments. The existence of a relation between X-ray emission and rotation has already been reported by Bouvier (1990), on the basis of REV 0 IPC data (see Paper I for a comparison between REV 0 and REV 1 data), and by ourselves (Damiani, Micela, & Vaiana 1991).

In our early report (Damiani et al. 1991) we presented a correlation between $L_x$ and $P_{rot}$. Photometric $P_{rot}$ values were available at that time for only 18 PMS stars in Taurus-Auriga, and it turned out that all those stars spanned a rather limited age range, being confined to ages younger than (1–2) $\times$ $10^6$ yr. For the remaining stars of the sample, with an estimated rotational period $P_{rot} \sim 2\pi R_*/(v \sin i)$, the previous correlation $L_x$-$P_{rot}$ was clearly absent, however, and we attributed that behavior to an age effect, the second subsample being on the average older than the former at the more than 3 $\sigma$ confidence level.

Since that report, new $P_{rot}$ measurements have been published (Bouvier et al. 1993), for stars spanning a wider age range than before (as well as a wider $P_{rot}$ range). We have therefore repeated our study of the relation $L_x$-$P_{rot}$, now finding a poorer correlation. Although for the whole sample the formal correlation coefficient $r_c$ is fairly good (with a probability of no correlation of $P = 0.047\%$), this depends largely on the X-ray–bright, rapidly rotating star HD 283572. If this star is omitted, the probability rises to $P = 0.98\%$, and almost no correlation remains visible. The comparison between this result and the correlation found by Damiani et al. (1991) suggests that, in order to find a correlation between $L_x$ and $P_{rot}$ for Taurus-Auriga T Tauri stars, one should examine smaller age-homogeneous subsamples rather than the whole available sample.

We choose therefore to first study the subsample with ages less than 2 $\times$ $10^6$ yr, for which a correlation was previously found. We estimated ages from the position in the H-R diagram, using evolutionary tracks computed by D'Antona & Mazzitelli (1994) and stellar bolometric luminosities taken from Cohen, Emerson, & Beichman (1989) and Walter et al. (1988) (see Table 1 of Paper I). The result is shown in Figure 1, including both old and new $P_{rot}$ measurements, where a fair correlation is visible. An estimate of errors in $L_x$ (§ 2.2 of Paper I) shows that it is dominated by uncertainties in the absorption correction ($\sim$50%) and that together with the error on distance and photon counting statistics this implies an overall error of 55%–65% for most sources. We have tested the statistical significance of the correlation using tests available in the ASURV package (Rev. 1.1; LaValley, Isobe, & Feigelson 1992; see also Isobe, Feigelson, & Nelson 1986), which take advantage of the information carried by nondetections as well, unlike the usual correlation coefficient. As a result, the probability that $L_x$ and $P_{rot}$ are not correlated, for stars younger than 2 $\times$ $10^6$ yr, is only $P = 0.02\%$, according to a Cox proportional hazard test, or $P = 0.12\%$, according to a Kendall's $\tau$-test. Using the same software, a best-fit to the data by the

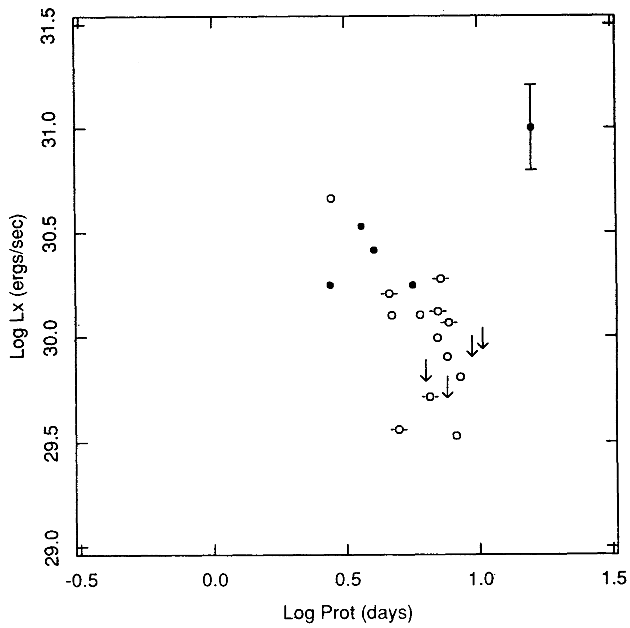


FIG. 1.—X-ray luminosity $L_x$ vs. rotational period $P_{rot}$, as derived from the photometry, for stars younger than $2 \times 10^6$ yr. In this and following figures, filled circles indicate stars undetected at 25 μm (WTTSs), while empty circles indicate stars detected at 25 μm (CTTSs). Small tick marks around a symbol indicate stars with ambiguous X-ray identification (Paper I). A representative error bar for $L_x$ is shown in the upper right corner. Arrows indicate upper limits on $L_x$.

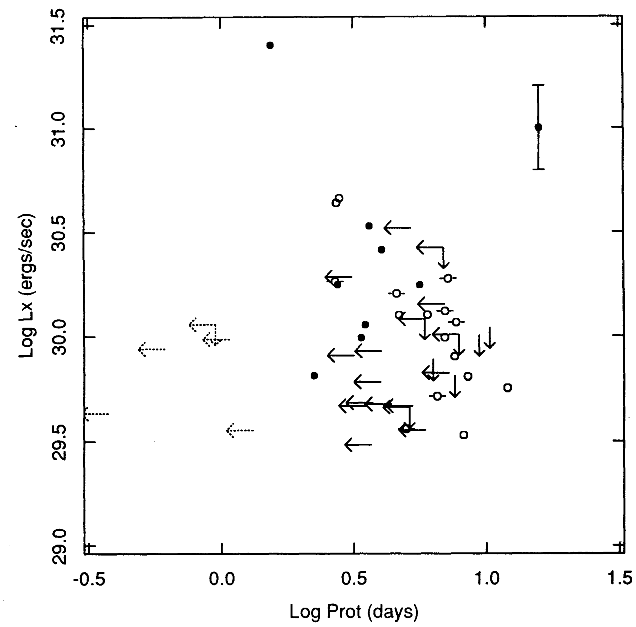


FIG. 2.—$L_x$ vs. $P_{rot}$ for the whole sample, including $P_{rot}$ estimates based on $v \sin i$ (*horizontal arrows*). Dotted arrows indicate stars where X-ray flux saturation takes place (see text). Other symbols as in Fig. 1.

parametric EM (Expectations-Maximization) algorithm was derived as:

$$\log L_x = 31.17 - 1.51 \log P_{rot} . \quad (1)$$

This correlation holds irrespective of the stellar mass.

In Figure 2, showing the relation between $L_x$ and $P_{rot}$ for the whole sample, no correlation above the 3 σ level is present (probabilities of no correlation are $P = 0.40\%$ [Cox test] and $P = 0.23\%$ [Kendall test], using photometric $P_{rot}$ only, and reach $P = 71.8\%$ and $P = 8.88\%$, respectively, using period estimates from $v \sin i$ as well). The physical reason for such a difference in the X-ray correlation properties as a function of the stellar age is not clear: it might be due to the evolving internal stellar structure, an issue hardly testable on observational grounds. Alternatively, if the X-ray flux cannot increase indefinitely during PMS contraction, the decrease of the stellar surface automatically leads to a decrease of the *total* emission due to coronal activity. This leads us to consider in this case the average X-ray surface flux $F_x$ as an appropriate diagnostic in this phase of stellar evolution. Incidentally, we think that the total X-ray luminosity $L_x$ is a directly measurable physical quantity, while $F_x$ is an *average* quantity and does not take into account volume effects; X-ray observations of the Sun have indeed clearly shown that even in the case of quite low $L_x$ the corona is strongly inhomogeneous over the surface and has a nonnegligible vertical extent.

We note that in Figure 2 a small number of fast-rotating stars (*dotted upper limits*) are very far from the best-fit relation (eq. [1]), being significantly underluminous for their $P_{rot}$. In a plot of X-ray flux $F_x$ versus $P_{rot}$ (Fig. 3), the same stars are seen to exhibit $F_x$-values within a factor of 3 of the maximum value for the whole sample (except again for HD 283572, which has a still higher $F_x$). This suggests that X-ray activity cannot increase indefinitely as stars rotate faster and faster, but rather levels off as soon as a "limiting" value of $F_x$ is reached, probably corresponding to a star completely covered by active regions. In our stars, such a saturation effect would be caused essentially by the decrease of the stellar radius, leading to the flattening of the $F_x$ versus $P_{rot}$ relation (Fig. 3), as well as to the appearance of the $L_x$ versus $P_{rot}$ plot of Figure 2.

The bulk of our sample stars, rotating less rapidly than those showing saturation effects, exhibits a dispersion in $F_x$ of nearly two orders of magnitude. A test applied to this sample (i.e., the whole sample except stars with $P_{rot} < 2$ days, thus excluding HD 283572) yields probabilities of no correlation of

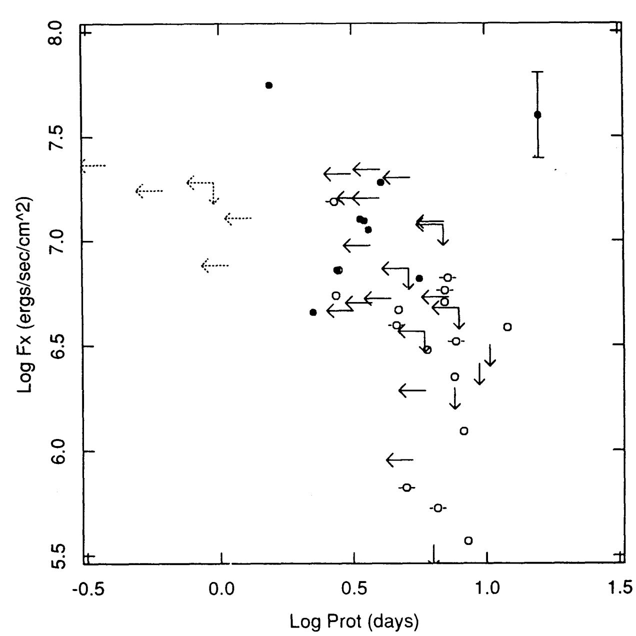


FIG. 3.—X-ray surface flux $F_x$ vs. $P_{rot}$. Symbols as in Fig. 1.

$P = 0.02\%$ (Cox test) and $P = 0.08\%$ (Kendall test) using photometric $P_{rot}$ only, and $P < 0.01\%$ (Cox test) and $P = 0.01\%$ (Kendall test) including $P_{rot}$ estimates from $v \sin i$. Therefore, the correlation between $F_x$ and $P_{rot}$ is at least as good as that between $L_x$ and $P_{rot}$ for the youngest stars. We note however that inspection of Figure 3 reveals that the relation log $F_x$–log $P_{rot}$ is not linear outside the above-explored $P_{rot}$ range, but flattens for rapidly rotating stars which attain the maximum $F_x$ values.

Given the number of independent parameters involved, it might seem at first sight appropriate to apply a multivariate (principal component) analysis. However, it is clear from Figure 3 that nonlinear effects (e.g., saturation) are at work and that therefore such an analysis would not give us meaningful results.

Finally, to strengthen our argument that saturation in the X-ray flux occurs, but is limited to some of the (older) stars, we plot in Figure 4 $F_x$ versus the stellar age. After an initial increase of $F_x$ with age, the X-ray flux levels off for stars older than about $10^6$ yr, at values in the range log $F_x \sim 7.0$–$7.5$ (ergs $s^{-1}$ $cm^{-2}$), supporting the view that at least some of these stars attain a limiting X-ray activity condition *in this age range*. For stars older than our sample and already on the main-sequence (with ages greater than $10^{7.5}$–$10^8$ yr), $F_x$ subsequently decreases with increasing age, as shown for example by Walter et al. (1988).

### 3.2. *Line Emission*

One relationship worth examining is that between X-ray emission and emission-line activity. In fact, practically all PMS stars exhibit emission lines at some level in the optical, UV, and IR spectral regions, among which the Hα line is the most conspicuous and can be taken as an indication of the stellar/circumstellar activity.

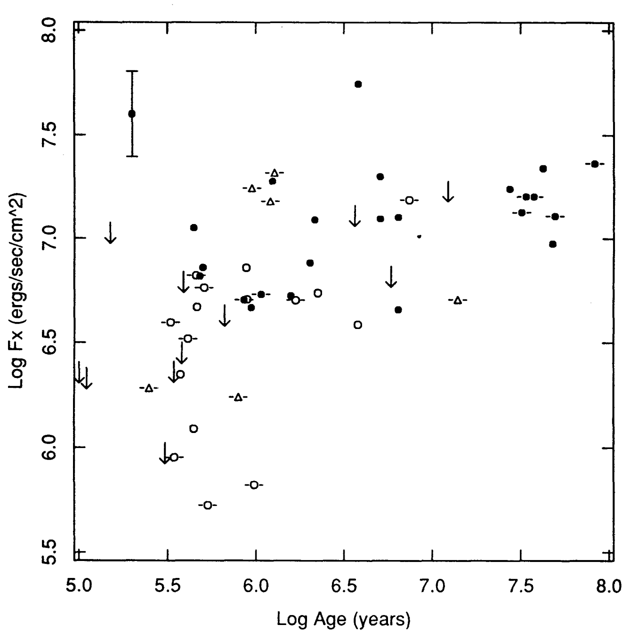


FIG. 4.—$F_x$ vs. stellar age. The topmost object is HD 283572; apart from this star, no sample star significantly exceeds log $F_x = 7.5$ ergs $s^{-1}$ $cm^{-2}$, which is likely to represent a maximum (saturation) X-ray flux. Here, and in the following figures, triangles are stars without 25 μm IR observations, and other symbols are as in Fig. 1.

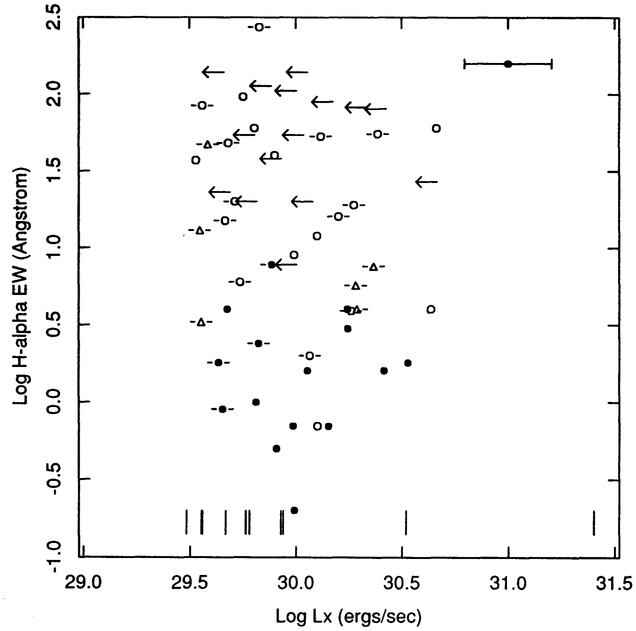


FIG. 5.—EW(Hα) vs. X-ray luminosity $L_x$. Symbols as in Fig. 4. In the lower part of the plot are indicated $L_x$-values for stars without a published value for the Hα equivalent width.

We have shown in Paper I that there is evidence of different distributions of X-ray luminosities (at the 99.6% confidence level) for classes of stars with widely different line emission properties, as measured using the Hα line equivalent width (EW). However, a scatter plot (Fig. 5) does not show a true anticorrelation between $L_x$ and Hα EW. This lack of correlation remains if we consider only stars detected (or undetected) at 25 μm, shown as empty (filled) symbols in Figure 5.

We mentioned in § 1 that Walter & Kuhi (1981) found an anticorrelation between $L_x$ and EW(Hα) for Taurus-Auriga stars and speculated that this might originate from absorption of part of the coronal X-ray emission by the same circumstellar material giving rise to the Hα emission. Feigelson & Kriss (1989), instead, found no correlation between the two quantities for their sample stars. Our results are intermediate between the two; namely, while strong and weak Hα emitters have different distributions of $L_x$ respectively (Paper I), no precise anticorrelation exists between $L_x$ and EW(Hα).

However, in the case of CTTSs, the Hα equivalent width may not be a meaningful indicator of activity. The reason for this is that the equivalent width measures the ratio between line and adjacent continuum emission, which in CTTSs unlike normal stars, do not arise from contiguous atmospheric layers. In fact, CTTS Hα line profiles indicate plasma velocities ≥100 km $s^{-1}$ (Hartmann 1982; Mundt 1984), with signatures of winds, or sometimes infall (e.g., Hartmann et al. 1982, 1990). For this reason, the equivalent width should be used with caution.

A quantity of more direct physical significance than the equivalent width is the actual luminosity in the line, above the continuum level; lacking high-resolution spectrophotometry, we have estimated it from the equivalent width itself, using for the continuum a value derived from the *R* magnitude (Herbig & Bell 1988), following the method devised by Young et al. (1989). This method allows a determination of the continuum with an accuracy of 4% for $T_{\rm eff}$ in the range 3000–4000 K. Since spectra and photometry are not simultaneous, this procedure may introduce some errors in the derived Hα luminosities.

For their WTTSs, Walter et al. (1988) considered the excess flux in the Hα line, above the absorption profile of corresponding spectral standards rather than above the extrapolated continuum. This procedure was also followed by Young et al. (1989) in their study of weak-emission dKe–dMe stars. We have therefore adopted it for the WTTSs, deriving the excess Hα *luminosities* from the values of surface flux and stellar radius tabulated by Walter et al. (1988). In the case of the CTTSs we have not attempted to compute Hα luminosities in this way because the implied corrections are of only a few percent, much smaller than the uncertainties already present.

A plot of $L_{\rm H\alpha}$ versus $L_x$ shows no relation at all for the whole sample (Fig. 6), although $L_{\rm H\alpha}$ and $L_x$ are correlated in the case of WTTSs (*filled dots*, Fig. 6; see § 3.2.2 below). A Wilcoxon test, applied to the two subsamples of stars having $L_{\rm H\alpha}$ respectively above and below $10^{30}$ ergs $\rm s^{-1}$, shows that these samples have X-ray luminosity distributions different only at the 75.5% confidence level. The stars T Tau, HL Tau, and SU Aur, among the brightest in both X-rays and Hα (although HL Tau has ambiguous X-ray identification), have been marked in Figure 6 to allow comparison with Figure 8 below. This also agrees very well with the lack of dependence of $L_x$ on the far-IR (25 μm) emission, shown in Figure 7 and discussed in Paper I: in fact, Cabrit et al. (1990) find that Hα and IR luminosities are well correlated for a large sample of T Tauri stars, and we have verified that this also holds for our sample stars.

It can also be seen in Figure 7 that the 25 μm flux values for the stars detected at 25 μm are fairly well separated from the low upper limits to the 25 μm flux of the undetected stars: therefore, from a purely observational point of view, a distinction between CTTSs and WTTSs is most clearly made with respect to their far-IR emission, rather than on the basis of their line emission, as the emission-line–related quantities show no such clear separation. This is in good agreement with the more physical arguments presented in § 2 in favor of an IR-based classification of these stars.

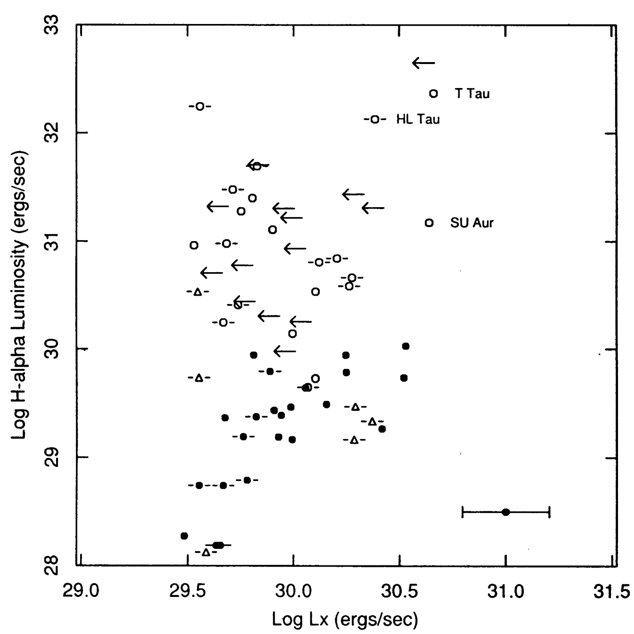


FIG. 6.—Hα line luminosity vs. X-ray luminosity $L_x$. The three stars with the largest $L_{\rm H\alpha}$ are labeled. Symbols as in Fig. 4.

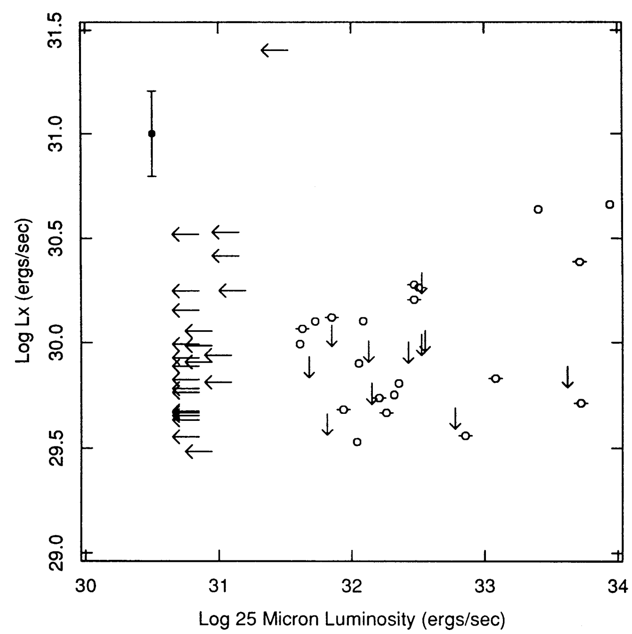


FIG. 7.—X-ray luminosity vs. *IRAS* luminosity at 25 μm (namely, in the 16–30 μm band); horizontal arrows are upper limits on $L_{25\,\mu\rm m}$.

### 3.2.1. *IR-detected Stars*

The connection of line emission activity with IR emission, and the presence of outflows, points definitely toward a nonstellar origin for the emission lines in CTTSs. We have argued on this basis above that the line equivalent width should not be considered a really meaningful quantity; on the other hand, given the existing correlation between line and IR luminosities, we try to define a quantity whose meaning is very similar to that of the equivalent width in the case of normal stars. Namely, as the latter is the (absorbed) line luminosity scaled to a continuum flux originating in nearly the same atmospheric region, we now define a quantity $\eta$ as the ratio of the Hα line luminosity to the luminosity in the 16–30 μm band, as deduced from the *IRAS* 25 μm measurements (Emerson 1988), $\eta \equiv \log (L_{\rm H\alpha}/L_{25\,\mu\rm m})$.

The quantity just defined can be viewed as the deviation from the average trend in a plot log $L_{\rm H\alpha}$–log $L_{25\,\mu\rm m}$. Of course, it has a meaning only in the case of the CTTSs, thereby forcing us to study separately the relation of line emission to X-ray emission in the case of weak-line stars. This is justified on the basis of the substantial differences in the circumstellar environments of IR-detected and undetected stars: IR-bright stars do correspond on average, to the class of stars with wind-originated line emission, while IR-undetected stars are generally weak-line stars.

When one deals with the parameter $\eta$ defined above, the statistics becomes poorer, as only about half our stars are IR sources. We show in Figure 8 the X-ray luminosity versus $\eta$: although a strict anticorrelation is not seen, the X-ray–brighter stars tend to have a lower $L_{\rm H\alpha}/L_{25\,\mu\rm m}$ ratio. To assess whether a statistically significant correlation exists, we should downweight stars with ambiguous identification, as their position in the $L_x$-$\eta$ scatter plot is affected by considerable uncertainty in both axes (the pairs are also unresolved by *IRAS* in the IR). It can be seen in Figure 8 that all well-identified stars (*circles*)

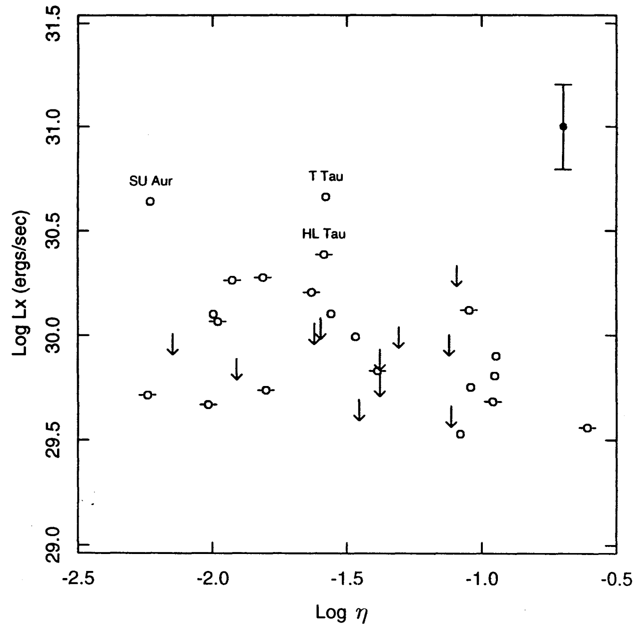


FIG. 8.—X-ray luminosity vs. $\eta$ ($\equiv \log L_{\mathrm{H}\alpha}/L_{25\,\mu\mathrm{m}}$). The three stars with the largest $L_{\mathrm{H}\alpha}$ are labeled, as in Fig. 6. Symbols as in Fig. 1.

with log $\eta < -1.5$ have larger X-ray luminosities than stars with log $\eta > -1.5$, but their small number prevents statistically valid results. The correlation coefficient computed considering unambiguous identifications alone is $r_c = -0.759$, which however corresponds to a probability of $L_x$ and $\eta$ being uncorrelated of $P = 1.8\%$.

A test which is probably less affected by errors in $L_x$ and $\eta$ for individual stars, and by the limited statistics, may be made by separating stars with $\eta$ above and below the median, respectively, and comparing their X-ray luminosity functions. Again, considering unambiguous identifications alone, a nonparametric Wilcoxon test yields a suggestive but not conclusive probability of 98.8% that the $L_x$ distributions are different. In order to include all stars, each with the proper weight, we have arbitrarily included each well-identified star twice in the luminosity function. The result is that the X-ray luminosity distributions for the two subsamples are different with a probability of 99.87%. Therefore, for stars having a fixed value for the 25 $\mu$m luminosity, the Hα luminosity is significantly lower when the X-ray emission is higher, on average, and vice versa. This might clarify the result of Paper I, where we found different X-ray luminosities for subsamples selected by a cutoff in the EW(Hα), but did not find any such difference for subsamples selected by a cutoff in the 25 $\mu$m flux. It is also interesting to note that the stars T Tau, HL Tau, and SU Aur have quite a low $\eta$—although they have large Hα luminosities—since their IR excess is very strong; therefore, the $\eta$-parameter we have defined allows us to look for properties that cannot be easily deduced from relationships with Hα or IR emission alone.

We remark that the measurements from which the anticorrelation between $L_x$ and $\eta$ has been found are not simultaneous, and the variability often detected in the X-ray, IR, and Hα emission of T Tauri stars tends to mask any existing relationship among these diagnostics themselves. Improvements in the study of the $L_x$ versus $\eta$ relationship could also be made with a better knowledge of line-of-sight absorption of X-rays and of the inclination of circumstellar disks.

### 3.2.2. *IR-undetected Stars*

Unlike the total sample, the X-ray and Hα luminosities are positively correlated for the subsample of stars undetected at 25 $\mu$m (*filled symbols*, Fig. 6). In order to check the validity of this correlation we have verified that a correlation exists as well between X-rays and other emission-line diagnostics, such as the Ca II H and K doublet. This has likely the same origin as Hα, as suggested by the correlation between Hα and Ca II H and K line luminosities in Figure 9 (the data on the Ca II H and K lines are taken from Calvet et al. 1985 for the CTTSs, and from Walter et al. 1988 for the WTTSs); we note that this correlation still holds for the subsample of WTTSs (*filled symbols*, Fig. 9). Therefore, Hα and Ca II H and K lines can be used as almost equivalent activity diagnostics.

We conclude that the (chromospheric) line emission of WTTSs is directly correlated with the X-ray luminosity, and this supports scenarios similar to the solar one, with an X-ray corona just above a chromospheric-like region, with some common heating mechanism at work, a conclusion already reached by various authors (Feigelson & Kriss 1981, 1989; Walter & Kuhi 1981, 1984; Walter et al. 1988; Bouvier 1990).

Although derived for WTTSs, this picture is not to be ruled out for the more active CTTSs, where any chromospheric (Hα or Ca II) emission would simply be masked by the stronger wind emission. In this sense, we agree with the point of view of Walter et al. (1988) that WTTSs (naked T Tauri stars) may provide direct information on purely stellar activity in PMS stars, which is hidden (*assuming it is present too*) in CTTSs by emissions from their complex circumstellar environment.

In the case of WTTSs we find that the X-ray luminosity is correlated not only with the emission-line luminosity, but also with the bolometric stellar luminosity $L_{\mathrm{bol}}$, a correlation which again disappears when considering the total sample (Fig. 10). Note that here we use values of $L_{\mathrm{bol}}$ taken from Cohen et al. (1989), computed excluding any nonstellar (disk) contribution to the total luminosity and therefore representative of the purely stellar bolometric emission. Some support for the existence of a physical correlation between X-ray and bolometric

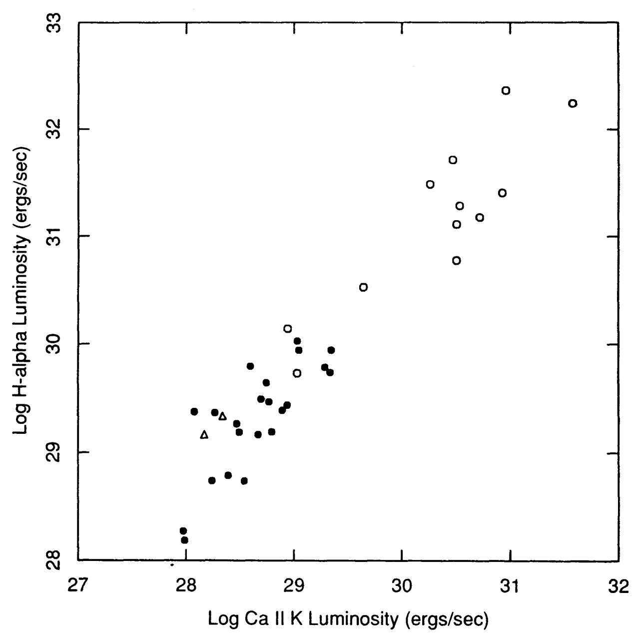


FIG. 9.—Hα vs. Ca II K line luminosities. Symbols as in Fig. 4.

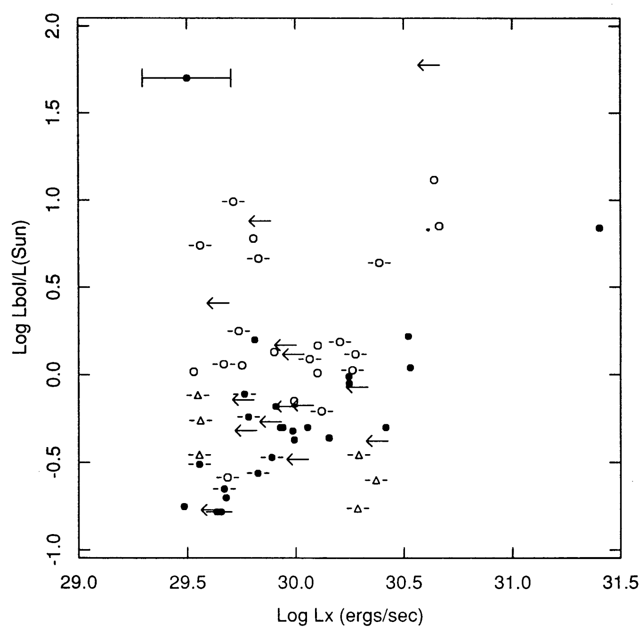


FIG. 10.—Stellar bolometric luminosity $L_{bol}$ vs. X-ray luminosity. Symbols as in Fig. 4.

luminosity for other late-type stars is given by the results of Young et al. (1989) and Pallavicini, Tagliaferri, & Stella (1990), who find such a correlation for the quiescent (i.e., nonflaring) X-ray luminosity of dKe–dMe stars. A related result is obtained by Barbera et al. (1993), who find that a correlation between $L_x$ and $L_{bol}$ holds for highly X-ray–luminous dMe stars and represents an upper envelope for the distribution of points in the ($L_x$, $L_{bol}$)-plane for a representative sample of K and M stars in the solar neighborhood. Weak-line T Tauri stars might therefore be analogous to dKe–dMe stars.

In a recent X-ray survey of the Chamaeleon I star-forming region using the *ROSAT* Position Sensitive Proportional Counter (PSPC), Feigelson et al. (1993) find that $L_x$ is strongly correlated with stellar bolometric luminosity, for both CTTSs and WTTSs. Although this result is apparently in contrast with our findings, it is not really so, given the different sensitivity limits of these data sets. This is clearly seen in Figure 10*a* of Feigelson et al. (1993), if we consider only that part of their sample with $L_x$ above our average detection threshold in Taurus-Auriga ($\sim \log L_x = 29.5$ ergs s$^{-1}$): for this subsample an $L_x$-$L_{bol}$ correlation remains visible for WTTSs, but no such correlation exists for the CTTSs, exactly as happens for our Taurus-Auriga sample. New, more sensitive X-ray data are needed on Taurus-Auriga PMS stars to compare their X-ray–optical correlation properties with those presented by Feigelson et al. (1993) for the Chamaeleon region.

## 4. DISCUSSION

### 4.1. *Origin of X-Ray Emission*

A common feature of stellar magnetic dynamo models is the dependence on the stellar rotation and surface convection of the effectiveness of the mechanism generating the magnetic field (Parker 1979). Therefore, chromospheric emission (Noyes et al. 1984) and X-ray emission (Pallavicini et al. 1981) of late-type stars, being correlated with the stellar rotation, have been claimed to have a magnetic origin.

T Tauri stars possess deep convection zones, and their X-ray emission is related to rotation, as seen in § 3.1 (eq. [1]). Therefore, the relation found is evidence of a dynamo origin for the X-ray emission of (Tau-Aur) T Tauri stars: the hot emitting plasma would be confined (and heated) by the magnetic field in some sort of closed field structures (loops), analogous to those well known to exist on the Sun, but more extended (or denser) and hotter to account for the different properties of the X-ray emission with respect to the solar case.

Our conclusion is therefore the same as that reached by Bouvier (1990), although he derives a slightly different relation between X-ray emission and rotation. Whatever the true form of the relation, there is little doubt that stellar rotation is essential to determining the level of X-ray emission in T Tauri stars.

In addition to the correlation with $P_{rot}$, other pieces of evidence point to a magnetic origin for X-ray emission in T Tauri stars: first, the X-ray–emitting plasma is too hot ($T \sim 10^7$ K; Paper I) to be confined on the stellar surface only by the gravity of the star. Second, it has been claimed (Cabrit et al. 1990) that X-ray emission, occurring with similar intensities for stars with and without strong emission-line (and accretion) activity, has an origin independent of accretion; this is also evident from our data (Fig. 7). Third, we note that 24 out of 28 stars (86%) showing a periodic modulation in their optical light curves, likely due to starspots, have been detected as X-ray sources. For the subset of CTTSs (i.e., stars detected at 25 $\mu$m), the X-ray detection fraction of stars showing starspots is 16/20 (80%), to be compared with the overall CTTSs detection statistic which is at most 62% (Paper I). Although the statistics is still limited, it appears therefore that stars with large surface spots, likely associated with strong magnetic fields (Bouvier & Bertout 1989), are also characterized by an enhanced level of X-ray emission, suggesting again a magnetic origin for this emission.

In the course of the development of this work, a possible alternative scenario has been proposed for the origin of the emission-line activity and the accretion process, the so-called magnetospheric model (Hartmann 1991; Königl 1991), where magnetic fields of sufficient strength disrupt the inner disk regions, stopping the orbital motion of the plasma and forcing it to follow magnetic field lines down to the stellar surface. This picture is supported by observational evidence of disks with inner holes (Beckwith et al. 1990; Skrutskie et al. 1990; Montmerle 1990), and also by observations of some "spots" hotter than the surrounding photosphere (Bouvier & Bertout 1989), identified as the basis of an "accretion column." Even in this case, therefore, spots are associated with strong surface magnetic fields, and the high X-ray detection fraction of spotted stars is an additional piece of evidence suggesting an association between magnetic fields and X-ray emission, independent of the relationship with stellar rotation discussed above.

### 4.2. *Weakening of* Hα *Emission*

One of the earliest works on X-ray emission from T Tauri stars proposed that the same circumstellar material giving rise to strong Hα emission absorbs a large fraction of the X-ray photons produced in a stellar corona (Walter & Kuhi 1981), on the basis of an anticorrelation the authors found between the X-ray luminosity and the Hα equivalent width. We also find a hint of such an anticorrelation, but only in an average sense (see § 3.2.1; and Paper I), and we now examine whether it can be uniquely due to selective X-ray absorption effects.

The X-ray luminosities obtained in Paper I take into account the line-of-sight absorption of X-rays, and therefore any absorption-related effects are, in principle, no longer present in our X-ray data, except for some of the stars being driven below the detection threshold and entering the sample as upper limits rather than as detections. Nevertheless, around T Tauri stars the gas-to-dust mass ratio may differ from the interstellar value assumed to compute $N_H$. If our estimates of the absorbing gas column density $N_H$ are unreliable, and if this is actually larger in strong emission-line stars, X-ray and line emission would appear anticorrelated only as a result of an improper absorption correction. However, if this were the case, we should observe not only a (slight) anticorrelation between $L_x$ and EW(H$\alpha$), but an even stronger one between $L_x$ and the H$\alpha$ line *luminosity*, which is a more direct measure of the hydrogen column density than the equivalent width. Of course, H$\alpha$ emission samples material in a large volume around the star, and not just along the line of sight (as $A_V$ does), but we stress that H$\alpha$ allows the sampling of circumstellar *gas*, relevant for X-ray absorption, unlike $A_V$ which samples *dust*. However, no anticorrelation between $L_x$ and H$\alpha$ line luminosity is observed at all (see § 3.2), and therefore we are confident of not having underestimated the X-ray absorption (and $L_x$) systematically for strong-line T Tauri stars.

Also, if our $L_x$-values were largely in error, we could probably not observe at all the quite tight relation with the rotational period we saw in § 3.1. Thus, all relations (or lack thereof) presented so far should not depend on improper absorption corrections and should rather reflect the true physical conditions of these stars.

To try to find a possible unifying, although qualitative, picture of CTTSs activity, we start with the consideration that magnetic fields seem to be implied by both X-ray and line emission. Indeed, the stellar winds where H$\alpha$ emission arises (according to some models) should be magnetized to account for the observed spin-down at the end of the contraction stage.

The magnetic field structures should be closed on relatively small scales in the case of X-ray–emitting loops, say less than a few stellar radii, while in the case of a wind they are approximately open. In the case of the magnetospheric model (Hartmann 1991; Königl 1991), most of the field lines are required to close in the stellar neighborhood to channel the orbiting disk matter toward the star, in any case with substantially larger length scales than those of coronal loops.

Assuming the classical wind picture, therefore, any plasma element in the outer atmospheric layers will be frozen to either closed or open field lines: in the first case it will remain confined and will be heated to high temperaures, to emit X-rays; in the second case, the gas will be pushed away in a wind by some mechanism, escaping from the star. In the case of the magnetospheric model, the plasma will behave as above in the relatively small, X-ray–emitting magnetic structures, while accretion through magnetic bundles is allowed only in those regions of the star surface where the field length scales are large enough to reach the disk. Therefore, "coronal" regions and regions where accretion (or wind emission) takes place are mutually exclusive in the magnetospheric model (or in the classical wind picture) (an analogous description has been proposed by Rosner et al. 1991 for the case of giants). The result is that, for a given star, there will be preferentially X-ray emission rather than (e.g., H$\alpha$) line emission, if magnetic field structures close predominantly on small scales typical of coronal loops.

This picture finds some observational support from the relation between $L_x$ and the quantity $\eta$, discussed in § 3.2.1. We claim now that we can use this ratio as a diagnostic of accretion (or wind) activity, not as an absolute measure of the degree of activity but rather as an indication of the process efficiency to produce H$\alpha$ emission. Namely, while both IR and H$\alpha$ luminosities should be proportional to the accretion rate $\dot{M}$, the H$\alpha$ luminosity also depends on such things as the fraction of the stellar surface coupled by magnetic field lines to the interstellar space or to the accretion disk itself. Therefore, the quantity $\eta$ should indicate whether the magnetic field structures above the star surface are indeed preferentially open or closed; in this sense, $\eta$ can be thought of as a diagnostic of the wind production efficiency (or accretion efficiency), regardless of the details of the physical picture.

The fact that the X-ray luminosity is on average inversely correlated with $\eta$ (§ 3.2.1) can therefore be taken as an observational confirmation of the suggested physical picture. Stars on which magnetic fields prevail in a closed topology are strong X-ray sources, but the effectiveness with which material is propelled in a wind and/or accreted (i.e., the wind production efficiency) is small; on the other hand, stars where magnetic structures of much larger scales dominate will have a small X-ray emission, but a large $\eta$ and wind production efficiency.

## 5. SUMMARY AND CONCLUSION

We have investigated the relationship of X-ray emission from T Tauri stars in the Taurus-Auriga star formation region with other stellar parameters, as well as their implications on our understanding of the structure of the stars' outer atmosphere and their immediate environment.

The X-ray luminosity turns out to be primarily determined by the stellar rotation period ($L_x \sim P_{rot}^{-2}$), suggesting a magnetic dynamo origin and qualitatively agreeing with the results of Bouvier (1990). However, for a given rotation rate, $L_x$ decreases with increasing age, thus following a trend similar to that well known to hold in the case of young main-sequence stars, such as Pleiades and Hyades (Micela et al. 1988, 1990).

We have discussed that the best way to separate high- from low-activity stars is through the IR emission. Indeed, according to current models, the presence of a substantial accretion activity should be ultimately responsible for the typically observed peculiarities of T Tauri stars.

If we consider the weak-emission stars, the correlation between the X-ray luminosity and that in the H$\alpha$ line points to a chromospheric origin for the latter and for the other weak emission lines of these stars. Further, the fact that the $L_x$ appears correlated with the bolometric luminosity, with ratios $L_x/L_{bol}$ close to the maximum values for the whole sample, might indicate that in these stars a saturation condition is reached, where the maximum possible fraction of the total energy output from the star is converted into X-rays.

Instead, for the stars with disks and strong line emission (CTTSs), our data suggest an inverse relation between the X-ray luminosity and the H$\alpha$ luminosity scaled to the 25 $\mu$m flux, a ratio which should indicate how efficient is the accretion process in supplying energy to the line-emitting gas, either in a stellar wind or in accretion columns. This efficiency should become greater as more of the star surface is covered by either open magnetic field structures, to let the gas escape freely, or large enough structures to couple the star and the disk at the distance of a few stellar radii. Therefore, the observed anticorrelation suggests that in some stars closed magnetic structures, where X-rays originate, prevail and inhibit an efficient conversion of the accreting matter energy into emission-line radiation; this takes place instead when larger scale magnetic fields exist and only few coronal, X-ray–emitting magnetic loops are present. This is somewhat reminiscent of the solar case, where regions of open field topology, the coronal holes, and closed coronal loops are seen to be mutually exclusive. The solar wind is emitted mainly from the open field regions, and the analogy could therefore be extended to PMS stars, although these have much larger mass-loss rates.

Since in the studied T Tauri stars rapid rotation may favor the formation of closed rather than open field structures, as inferred from the X-ray emission levels, it may also reduce the braking of the star by a magnetized wind (e.g., Collier Cameron, Jianke, & Mestel 1991). If at the same time angular momentum is supplied to the star by the accretion disk, a situation may be established in which the rotation rate, if higher than a given threshold, will grow as long as accretion takes place, because the dynamo-generated field would form mainly closed structures and the braking provided by the wind will be small. When instead the initial rotation rate is lower than the threshold, braking might remove more angular momentum than supplied by the disk, and the star will slow down until the end of the accretion-wind phase.

To resolve many of the ambiguities encountered, more observational data are required. An enlargement of the X-ray–observed sample will be possible with the use of new *ROSAT* data. In addition, the search for even small photometric modulations in the optical light of these stars, especially the WTTSs, to detect their rotational periods, would yield more detailed information about the relationship between X-ray emission and rotation. Further, to reduce any scatter possibly due to long-term variability, simultaneous X-ray and optical observations will be necessary. On shorter timescales, it would be very interesting to look for rotational modulations of both the X-ray and Hα emissions, and for their phase relations; this could confirm our suggestion that in every region of these stars' surfaces the conditions for having X-ray or Hα emission are mutually exclusive.

Last, the problem of how much of the emitted X-rays are absorbed should be more carefully addressed, that is, whether the current usage of deriving the hydrogen column density from the optical extinction retains its validity in the neighborhood of such complex systems. Alternatively, one could deduce the X-ray absorption *directly* from X-ray observations if data with sufficiently high S/N and spectral resolution are available. While this may be done for only a few stars with *Einstein* IPC data, we expect that the analysis of *ROSAT* PSPC data will give an answer to this problem for a larger number of cases.

This work was inspired by the late G. S. Vaiana, who took part in its early development and without whose contribution this paper might never have been written.

We acknowledge support by the Italian Ministero per la Ricerca Scientifica e Tecnologica, and from Agenzia Spaziale Italiana. Fruitful discussions with S. Serio and S. Sciortino on the content and presentation of this paper are also gratefully acknowledged. Thanks are due to the referee and to T. Simon, whose suggestions have allowed us to improve this paper.

## REFERENCES


Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 321, 788
Barbera, M., Micela, G., Sciortino, S., Harnden, F. R., Jr., & Rosner, R. 1993, ApJ, 414, 846
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924
Bertout, C., Basri, G., & Bouvier, J. 1988, ApJ, 330, 350
Bouvier, J. 1990, AJ, 99, 946
Bouvier, J., & Bertout, C. 1989, A&A, 211, 99
Bouvier, J., Cabrit, S., Fernandez, M., Martin, E. L., & Matthews, J. M. 1993, A&A, 272, 176
Cabrit, S., Edwards, S., Strom, S. E., & Strom, K. M. 1990, ApJ, 354, 687
Caillault, J.-P., & Helfand, D. J. 1985, ApJ, 289, 279
Calvet, N., Basri, G., Imhoff, G. L., & Giampapa, M. S. 1985, ApJ, 293, 575
Calvet, N., Basri, G., Kuhi, L. V. 1984, ApJ, 277, 725
Cohen, M., Emerson, J. P., & Beichman, C. A. 1989, ApJ, 339, 445
Collier Cameron, A., Jianke, L., & Mestel, L. 1991, in Angular Momentum Evolution of Young Stars, ed. S. Catalano & J. Stauffer (Dordrecht: Kluwer), 297
Damiani, F., Micela, G., Sciortino, S., & Harnden, F. R. 1995, ApJ, 446, 331 (Paper I)
Damiani, F., Micela, G., & Vaiana, G. S. 1991, in Angular Momentum Evolution of Young Stars, ed. S. Catalano & J. Stauffer (Dordrecht: Kluwer), 89
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
Emerson, J. P. 1988, in Formation and Evolution of Low-Mass Stars, ed. A. K. Dupree & M. T. V. T. Lago (Dordrecht: Kluwer), 193
Feigelson, E. D., Casanova, S., Montmerle, T., & Guibert, J. 1993, ApJ, 416, 623
Feigelson, E. D., & Kriss, G. A. 1981, ApJ, 248, L35
———. 1989, ApJ, 338, 262
Fleming, T. A., Gioia, I. M., & Maccacaro, T. 1989, ApJ, 340, 1011
Harris, S., Clegg, P., & Hughes, J. 1988, MNRAS, 235, 441
Hartmann, L. 1982, ApJS, 48, 109
———. 1991, in Angular Momentum Evolution of Young Stars, ed. S. Catalano & J. Stauffer (Dordrecht: Kluwer), 379
Hartmann, L., Calvet, N., Avrett, E. H., & Loeser, R. 1990, ApJ, 349, 168
Hartmann, L., Edwards, S. L., & Avrett, E. H. 1982, ApJ, 261, 279
Herbig, G. H., & Goodrich, R. W. 1986, ApJ, 309, 294
Herbig, G. H., & Bell, K. R. 1988, Third Catalog of Emission-Line Stars of the Orion Population (Lick Obs. Bull. 1111)
Isobe, T., Feigelson, E. D., & Nelson, P. I. 1986, ApJ, 306, 490
Königl, A. 1991, ApJ, 370, L39
LaValley, M., Isobe, T., & Feigelson, E. D. 1992, BAAS, 24, 839
Maggio, A., Sciortino, S., Vaiana, G. S., Majer, P., Bookbinder, J., Golub, L., Harnden, F. R., & Rosner, R. 1987, ApJ, 315, 687
Micela, G., Sciortino, S., Vaiana, G. S., Harnden, F. R., Rosner, R., & Schmitt, J. H. M. M. 1990, ApJ, 348, 557
Micela, G., Sciortino, S., Vaiana, G. S., Schmitt, J. H. M. M., Stern, R. A., Harnden, F. R., & Rosner, R. 1988, ApJ, 325, 798
Montmerle, T. 1990, in Reviews in Modern Astronomy, ed. G. Klare (Berlin: Springer), 3, 209
Mundt, R. 1984, ApJ, 280, 749
Noyes, R. W., Hartmann, L. W., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Pallavicini, R., Golub, L., Rosner, R., Vaiana, G. S., Ayres, T. R., & Linsky, J. L. 1981, ApJ, 248, 279
Pallavicini, R., Tagliaferri, G., & Stella, L. 1990, A&A, 228, 403
Parker, E. N. 1979, Cosmical Magnetic Fields (Oxford: Clarendon)
Rosner, R., An, C., Musielak, Z. E., Moore, R. L., & Suess, S. T. 1991, ApJ, 372, 91
Rydgren, A. E., & Vrba, F. J. 1981, AJ, 86, 1069
———. 1983, AJ, 88, 1017
Schachter, J. F., Remillard, R., Saar, S., Favata, F., Sciortino, S., & Barbera, M. 1995, ApJ, submitted
Skrutskie, M. F., Dutkevitch, D., Strom, S. E., Edwards, S., Strom, K. M., & Shure, M. A. 1990, AJ, 99, 1187
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451
Strom, K. M., Strom, S. E., Kenyon, S. J., & Hartmann, L. 1988, AJ, 95, 534
Walter, F. M., Brown, A., Mathieu, R. D., Myers, P. C., & Vrba, F. J. 1988, AJ, 96, 297
Walter, F. M., & Kuhi, L. V. 1981, ApJ, 250, 254
———. 1984, ApJ, 284, 194
Young, A., Skumanich, A., Stauffer, J. R., Bopp, B. W., & Harlan, E. 1989, ApJ, 344, 427