EINSTEIN Observations of T Tauri Stars in Taurus-Auriga. II: Relationships between X-ray Emission and Pre-Main-Sequence Activity

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Abstract

On the basis of the full set of reanalyzed *Einstein* IPC X-ray data on Tau-Aur 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 on the origin of the X-ray emission and on 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 find also 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, holds limitedly to stars younger than $2 \cdot 10^6$ 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 (WTTS), instead, a correlation between X-ray- and un-scaled Hα luminosity is found, providing further evidence for the chromospheric origin of the line emission in these latter stars.

Subject headings: stars: coronae – stars: pre-main-sequence – X-rays: stars

1. Introduction

We have presented in a companion paper (Damiani et al. 1994, 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 consideration of the statistical significance of the various results. By considering the subsamples of strong and weak emission line stars, a difference was found 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 pre-main-sequence 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 (CTTS) in Tau-Aur; 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). It is however still worthwhile to reconsider these correlations, since Bouvier (1990) generally uses X-ray data coming from the early (Rev 0) release of *Einstein* data, and 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. section 2.2 of Paper I) reveals that in a fraction of cases Rev 1 changes significantly the deduced source rates.

In Section 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 Section 4. Section 5 is a summary of the main results obtained.

2. The 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 12μ, 25μ, 60μ and 100μ. 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 towards the stellar photospheres ($A_V \sim$ 1-2 mags), 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 and with an often 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 profiles (e.g. Hartmann, Edwards & Avrett 1982, Hartmann et al. 1990), which deep-chromosphere models failed to explain (Calvet, Basri & Kuhi 1984). Enhanced-chromosphere models seem instead appropriate to reproduce emission lines in weak-line T Tauri stars (WTTS), 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 classical T Tauri stars, are 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 right 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 for allowing to look 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 diagnostics of this accretion activity. A much more direct way to look at the source of activity, therefore, is to study directly the disk emission at infrared wavelengths (Adams, Lada & Shu 1987). Between 25μ and 60μ 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 about 0.1 Jy) at 25μ as two classes of physically different objects. Henceforth, we will therefore call 'classical' (CTTS) and 'weak-line' T Tauri stars (WTTS), respectively, stars detected and undetected by IRAS at 25μ, rather than follow the more common usage of regrouping stars according to their Hα 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 generally late-type stars are found to obey is of the kind $L_x \propto (v \sin i)^2$, independently 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 EMSS (Fleming, Gioia and Maccacaro 1989), and in the *Einstein Slew Survey* (Schachter et al. 1994).

In order to study to what extent such relations hold for our T Tauri star sample, we have searched in the published literature rotational periods (P_{rot}) for the sample stars, as reported in Table 1 of Paper I. The use of periods deduced from periodic photometric lightcurves 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 been reported already 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 and Vaiana 1991).

In our early report (Damiani, Micela and Vaiana 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 Tau-Aur, and it turned out that all those stars spanned a rather limited age range, being confined to ages younger than $1 - 2 \cdot 10^6$ yr. For the remaining stars of the sample, estimating the rotational period as $P_{rot} \sim 2\pi R_\star / v \sin i$, the previous correlation L_x-P_{rot} was clearly absent, however, and we attributed that behaviour to an age effect, being the second subsample on the average older than the former, at more than 3σ 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} , finding now a poorer correlation: although for the whole sample the formal correlation coefficient r_c is fairly good (with probability of no correlation P=0.047%), this depends largely on the X-ray bright, rapidly rotating star HD 283572: omitting this star the probability rises to P=0.98%, and almost no correlation remains visible. The comparison between this result and the correlation found by Damiani, Micela and Vaiana (1991) suggests that, in order to find a correlation between L_x and P_{rot} for Tau-Aur 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 age less than $2 \cdot 10^6$ yr, for which a correlation was previously found. We estimated ages from the position in the HR 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 on L_x (section 2.2 of Paper I) shows that it is dominated by uncertainties in the absorption correction (~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 non-detections 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 $2 \cdot 10^6$ yr, is only P=0.02%, according to a Cox proportional hazard test, and P=0.12% according to a Kendall's tau test. Using the same software, a best fit to the data by the parametric EM algorithm was derived as:

$$\log L_x = 31.17 - 1.51 \, \log P_{rot}. \tag{1}$$

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 3σ level is instead 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 also period estimates from $v \sin i$). The physical reason of 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 diagnostics 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 non-negligible vertical extent.

We note that in Figure 2 a small number of fast rotating stars (dotted upper limits in the figure) 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 vs. P_{rot} (Figure 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 saturation effect would be caused essentially by the decrease of the stellar radius, leading to the flattening of the F_x vs. P_{rot} relation (Figure 3), as well as to the appearance of the L_x vs. 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 also HD 283572) yields probabilities of no correlation of 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 however note 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 non-linear 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 limitedly to some of the (older) stars, we plot in Figure 4 F_x vs. 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 age 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 pre-main-sequence 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 indication of the stellar/circumstellar activity.

We have shown in Paper I that there is evidence of a different distribution 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 (Figure 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 25μ, shown as empty (filled) symbols in Figure 5.

We mentioned in Section 1 that Walter & Kuhi (1981) find an anticorrelation between L_x and EW(Hα) for Tau-Aur stars, and speculate 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 and Kriss (1989), instead, find no correlation between the two quantities for their sample stars. Our results are intermediate betwen the two; namely, while strong and weak Hα emitters have different distributions of L_x (Paper I), no precise anticorrelation exists between L_x and EW(Hα).

However, in the case of classical T Tauri stars, 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 classical T Tauri stars, unlike normal stars, do not arise from contiguous atmospheric layers. In fact, CTTS Hα line profiles indicate plasma velocities $\geq$ 100 km/sec (Hartmann 1982, Mundt 1984), with signatures of winds, or sometimes infall (e.g. Hartmann, Edwards & Avrett 1982, Hartmann et al. 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 EW 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_{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 WTTS, Walter et al. (1988) have considered the excess flux in the Hα line, above the absorption profile of corresponding spectral standards rather than above the extrapolated continuum. This procedure has also been followed by Young et al. (1989) in their study of weak-emission dKe-dMe stars. We have therefore adopted it for WTTS, 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 CTTS 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 $L_{H\alpha}$ vs. L_x shows no relation at all for the whole sample (Figure 6), although $L_{H\alpha}$ and L_x are correlated in the case of WTTS (filled dots in Figure 6; see section 3.2.2 below). A Wilcoxon test, applied to the two subsamples of stars having $L_{H\alpha}$ respectively above and below 10^{30} ergs/sec, 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 (25μ) 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 25μ-flux values for the stars detected at 25μ are fairly well separated from the low upper limits to the 25μ-flux of the undetected stars: therefore, from a purely observational point of view, a distinction between CTTS and WTTS is most clearly done 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 Section 2 in favor of an IR-based classification of these stars.

3.2.1 IR-Detected Stars

The connection of line emission activity with infrared emission, and the presence of outflows points definitely towards a nonstellar origin for the emission lines in CTTS. On this basis we have argued above not to consider the line equivalent width a really meaningful quantity; on the other hand, given the existing correlation between line and infrared 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 originated in nearly the same atmospheric region, we now define a quantity η as the ratio of the Hα line luminosity over the luminosity in the 16-30μ band, as deduced from the IRAS 25μ measurements (Emerson 1988), $\eta \equiv \log(L_{H\alpha}/L_{25\mu})$.

The quantity just defined can be viewed as the deviation from the average trend in a plot $\log L_{H\alpha}$-$\log L_{25\mu}$. Of course, it has a meaning only in the case of the CTTS, thereby forcing us to study separately the relations of line- 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 the 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 η defined above, the statistics becomes poorer, as only about half of our stars are IR sources. We show in Figure 8 the X-ray luminosity vs. η: although a strict anticorrelation is not seen, the X-ray brighter stars tend to have a lower $L_{H\alpha}/L_{25\mu}$ ratio. To assess if a statistically significant correlation exists, we should down-weight 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 infrared). It can be seen in Figure 8 that all well-identified stars (circles) with $\log \eta < -1.5$ have larger X-ray luminosities than stars with $\log \eta > -1.5$, but their small number prevents to reach 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 η being uncorrelated of P=1.8%.

A test which is probably less affected by errors on L_x and η for individual stars, and by the limited statistics, may be made by separating stars with η 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 twice each well-identified star 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 25μ luminosity, the Hα luminosity is significantly lower when the X-ray emission is higher, on the 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 25μ flux. It is also interesting to note that the stars T Tau, HL Tau and SU Aur have quite a low η, although they have large Hα luminosities, since their IR excess is very strong; therefore, the η parameter we have defined allows us to look for properties that cannot easily deduced from relationships with Hα or IR emission alone.

We remark that the measurements from which the anticorrelation between L_x and η 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 vs. η relationship could be made also 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 25μ (filled symbols in Figure 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&K doublet. This has likely the same origin as Hα, as suggested by the correlation between Hα and Ca II H&K line luminosities of Figure 9 (the data on the Ca II H&K lines are taken from Calvet et al. 1985 for the CTTS, and from Walter et al. 1988 for the WTTS); we note that this correlation still holds for the subsample of WTTS (filled symbols in Figure 9). Therefore, Hα and Ca II H&K lines can be used as almost equivalent activity diagnostics.

We conclude that the (chromospheric) line emission of WTTS 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, Walter & Kuhi 1981, 1984, Walter et al. 1988, Feigelson & Kriss 1989, Bouvier 1990).

Although derived for WTTS, this picture is not to be ruled out for the more active CTTS, where any chromospheric (Hα, 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 weak-lined T Tauri stars ('naked T Tauri stars') may provide direct information on purely stellar activity in PMS stars, which is hidden (*assuming it is present too*) in CTTS by emissions from their complex circumstellar environment.

In the case of WTTS we find that the X-ray luminosity is correlated not only with the emission line luminosity, but also with the bolometric stellar luminosity L_{bol}, a correlation which again disappears when considering the total sample (Figure 10). Note that we here use values of L_{bol} taken from Cohen, Emerson & Beichman (1989), computed excluding any non-stellar (disk) contribution to the total luminosity, and therefore representative of the purely stellar bolometric emission. Some support to the existence of a physical correlation between X-ray and bolometric luminosity for other late-type stars is given by the results of Young et al. (1989) and Pallavicini, Tagliaferri & Stella (1990), who find such 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 PSPC, Feigelson et al. (1993) find that L_x is strongly correlated with stellar bolometric luminosity, for both CTTS and WTTS. Although this result is apparently in contrast with our findings, it is not really so, given the different sensitivity limits of these datasets. 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 Tau-Aur ($\sim \log L_x = 29.5$ ergs/sec): for this subsample a $L_x - L_{bol}$ correlation remains visible for WTTS, but no such correlation exists for the CTTS, exactly as it happens for our Tau-Aur sample. New, more sensitive X-ray data are needed on Tau-Aur pre-main-sequence 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 *The 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 Section 3.1 (eq. 1). Therefore, the relation found is an 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 anyway that stellar rotation is essential to determine the level of X-ray emission in T Tauri stars.

Besides 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 from accretion; this is also evident from our data (Figure 7). Third, we note that 24 out of 28 stars (86%) showing a periodic modulation in their optical lightcurves, likely due to starspots, have been detected as X-ray sources. For the subset of CTTS (i.e. stars detected at 25μ), the X-ray detection fraction of stars showing starspots is 16/20 (80%), to be compared with the overall CTTS 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 latter.

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 association between magnetic field and X-ray emission, independent of the relationship with stellar rotation discussed above.

4.2 *The Weakening of Hα Emission*

In one of the earliest works on X-ray emission from T Tauri stars it was 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 these 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 Section 3.2.1, and Paper I), and we now examine if 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(Hα), but an even stronger one between L_x and the Hα line *luminosity*, which is a more direct measure of the hydrogen column density than the equivalent width. Of course, Hα 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 Hα allows to sample circumstellar *gas*, relevant for X-ray absorption, unlike A_V which samples *dust*. However, no anticorrelation between L_x and Hα line luminosity is observed at all (see Section 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 have seen in Section 3.1. Thus, all relations (or lack thereof) presented so far should not depend on improper absorption corrections, and rather reflect the true physical conditions of these stars.

To try to find a possible unifying, although qualitative, picture of CTTS 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 Hα 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 towards the star, anyway with substantially larger lengthscales 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 temperatures, to emit X-rays; in the second one, 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 lengthscales 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. Hα) 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 η, discussed in Section 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 Hα emission. Namely, while both IR- and Hα luminosities should be proportional to the accretion rate $\dot{M}$, the Hα 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 η should indicate if the magnetic field structures above the star surface are indeed preferentially open or closed; in this sense η can be thought of as a diagnostics 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 the average inversely correlated with η (Section 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 η 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 their 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, like 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 infrared emission. Indeed, according to current models, the presence of a substantial accretion activity should be ultimately responsible for the typically observed T Tauri stars peculiarities.

Considering the weak-emission stars, the correlation between the X-ray luminosity and that in the Hα 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 in X-rays.

Instead, for the stars with disks and strong line emission ('classical' T Tauri stars), our data suggest an inverse relation between the X-ray luminosity and the Hα luminosity scaled to the 25μ 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 be 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 prevail, where X-rays originate, and inhibit an efficient conversion of the accreting matter energy into emission-line radiation; this instead takes place 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 latter 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 WTTS, 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' surface the conditions for having X-ray or Hα emission are mutually exclusive.

Last, the problem of how much the emitted X-ray 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.

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 contents and presentation of this paper are also gratefully acknowledged. Thanks are due to an anonymous referee and to T.Simon, whose suggestions have allowed us to improve this paper as well.

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Figure Captions.

Figure 1. X-ray luminosity L_x vs. rotational period P_{rot}, as derived from the photometry, for stars younger than $2 \cdot 10^6$ yr. In this and following figures, filled circles indicate stars undetected at 25μ (WTTS), while empty circles are stars detected at 25μ (CTTS). 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.

Figure 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 Figure 1.

Figure 3. X-ray surface flux F_x vs. P_{rot}; symbols have the same meaning as in Figure 1.

Figure 4. F_x vs. stellar age. The topmost object is HD 283572; apart from this star, no sample star signicantly exceeds $\log F_x = 7.5$ ergs/sec cm^2, which is likely to represent a maximum (saturation) X-ray flux. Here, and in the following Figures, triangles are stars without 25μ IR observations, and other symbols are as in Figure 1.

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

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

Figure 7. X-ray luminosity vs. IRAS luminosity at 25μ (namely, in the 16-30μ band); horizontal arrows are upper limits on $L_{25\mu}$.

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

Figure 9. Hα- vs. Ca II K line luminosities. Symbols as in Figure 4.

Figure 10. Stellar bolometric luminosity L_{bol} vs. X-ray luminosity. Symbols as in Figure 4.

Figure 1

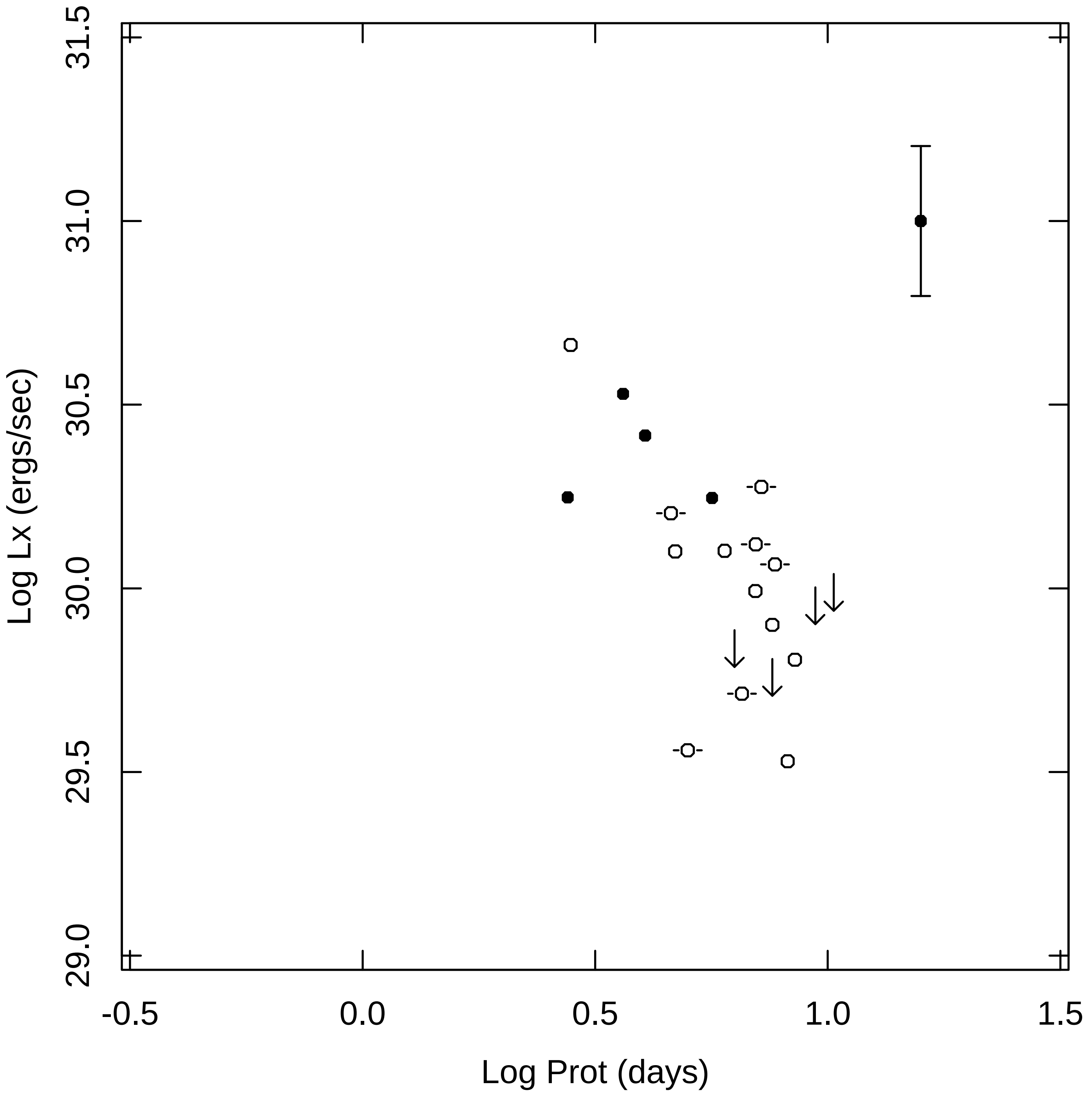
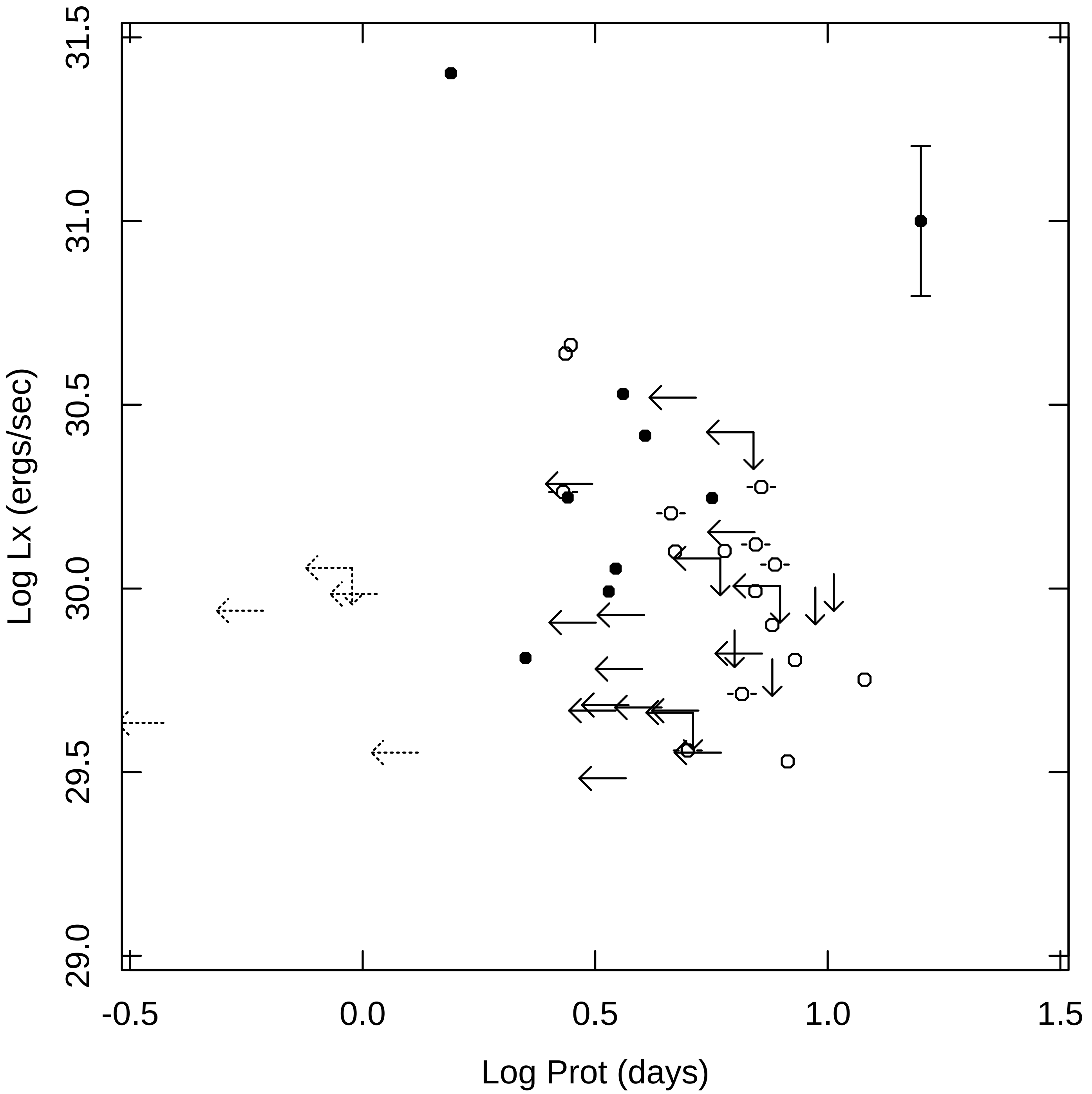

Log Lx (ergs/sec)
31.5
31.0
30.5
30.0
29.5
29.0
-0.5
0.0
0.5
1.0
1.5
Log Prot (days)

Figure 2



31.5
31.0
30.5
30.0
29.5
29.0
Log Lx (ergs/sec)
-0.5
0.0
0.5
1.0
1.5
Log Prot (days)

Figure 3

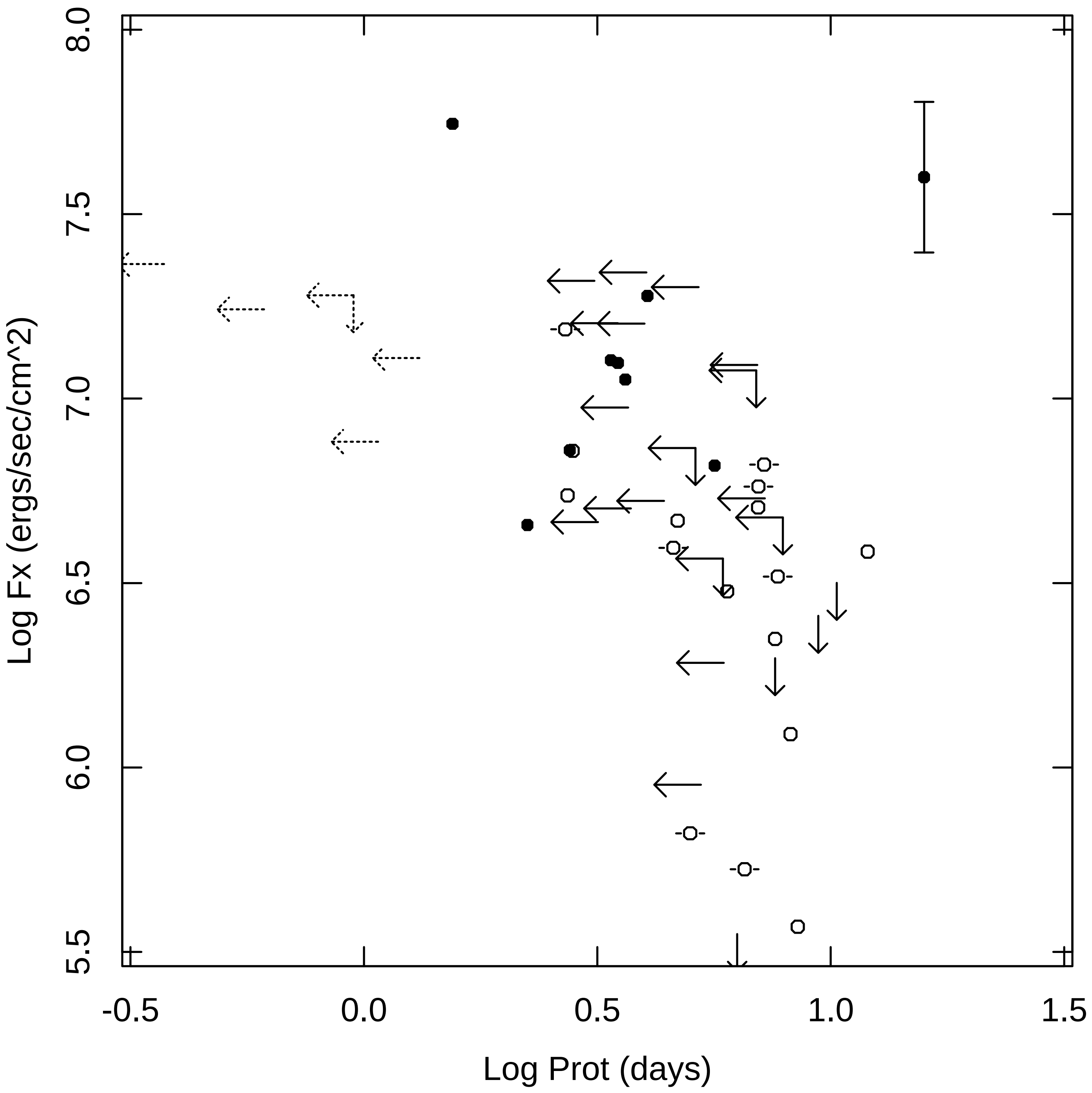


Figure 4

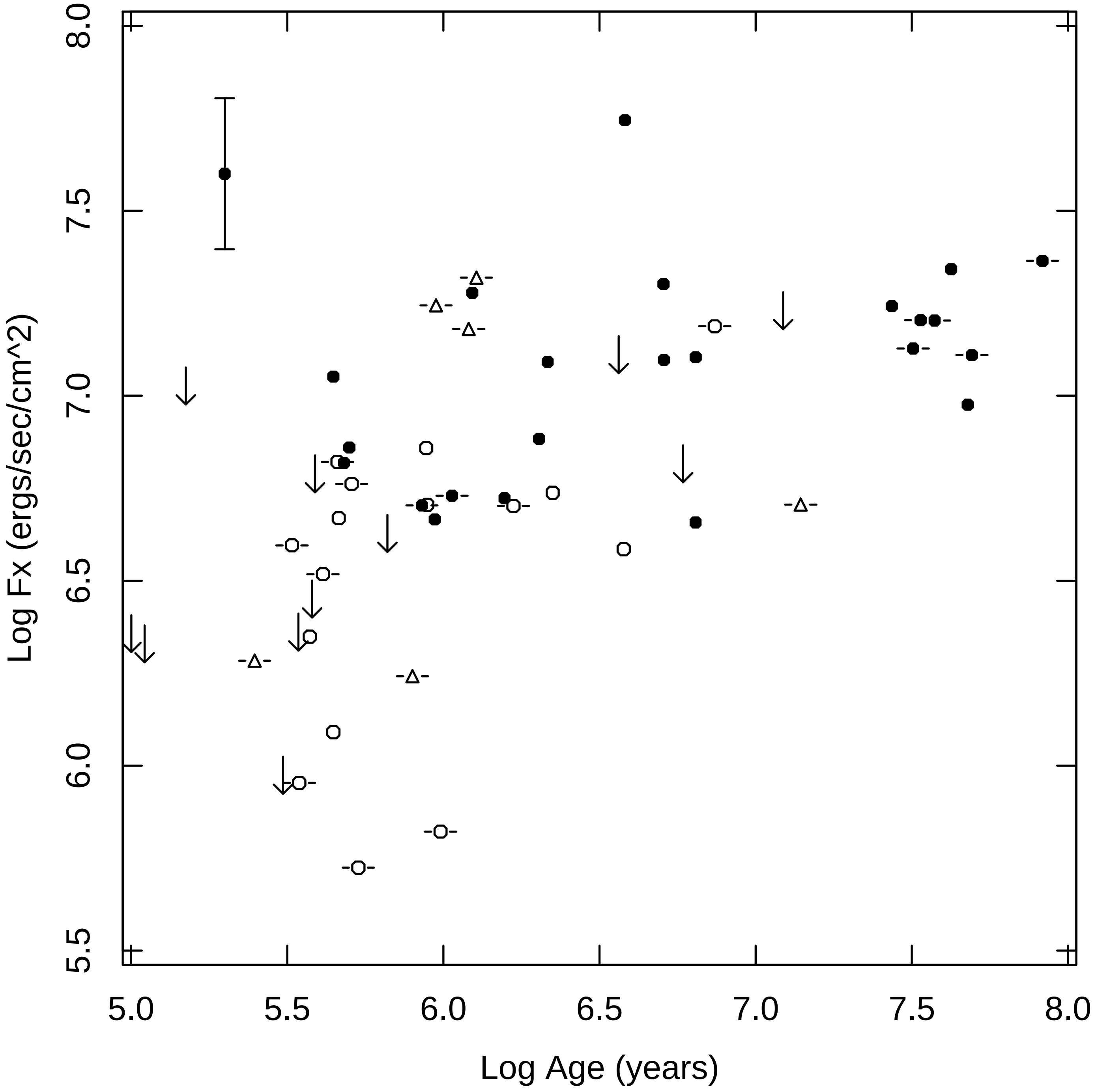
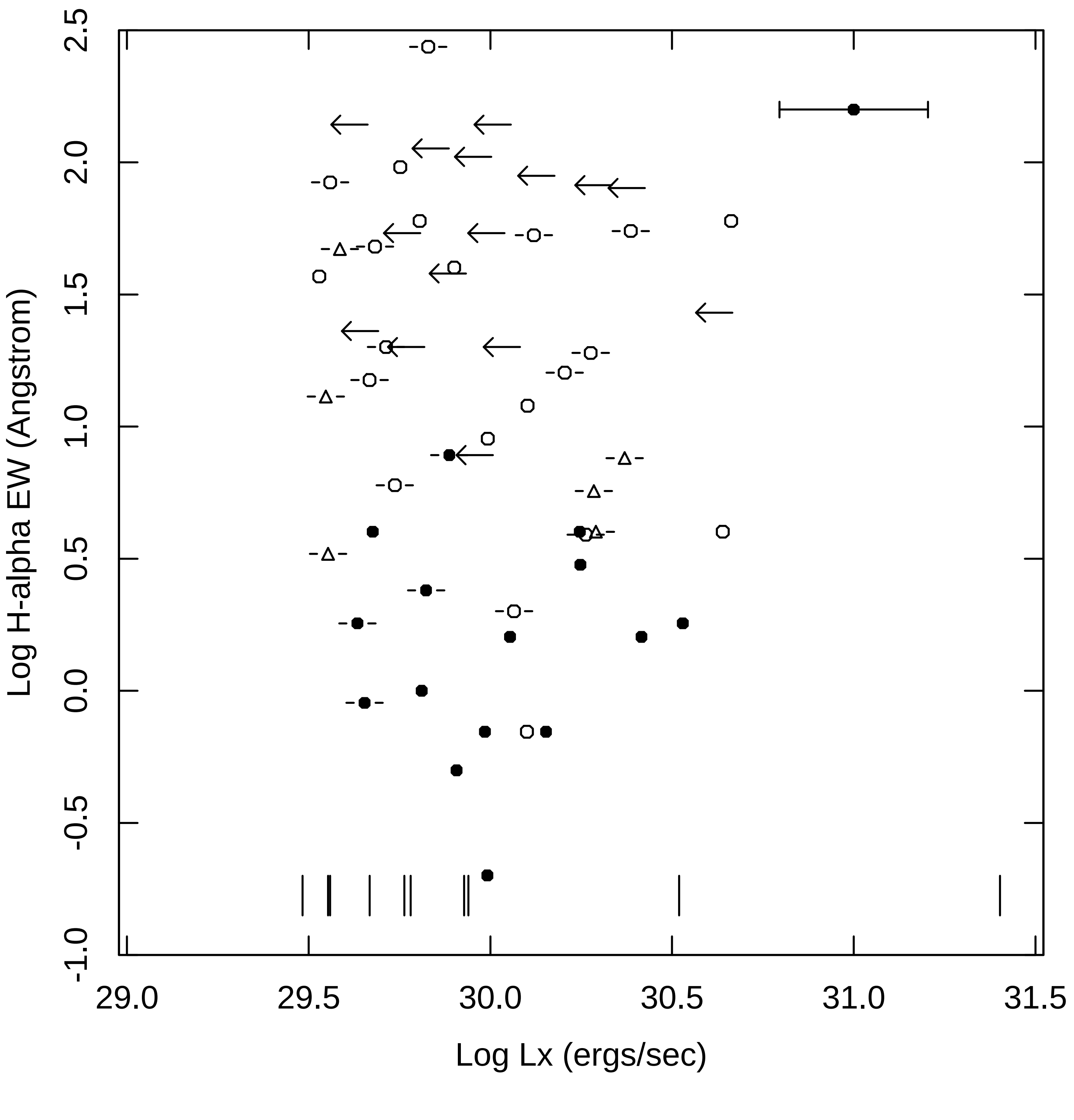

8.0
7.5
7.0
6.5
6.0
5.5
Log Fx (ergs/sec/cm^2)
5.0
5.5
6.0
6.5
7.0
7.5
8.0
Log Age (years)

Figure 5



Log H-alpha EW (Angstrom)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
29.0
29.5
30.0
30.5
31.0
31.5
Log Lx (ergs/sec)

Figure 6

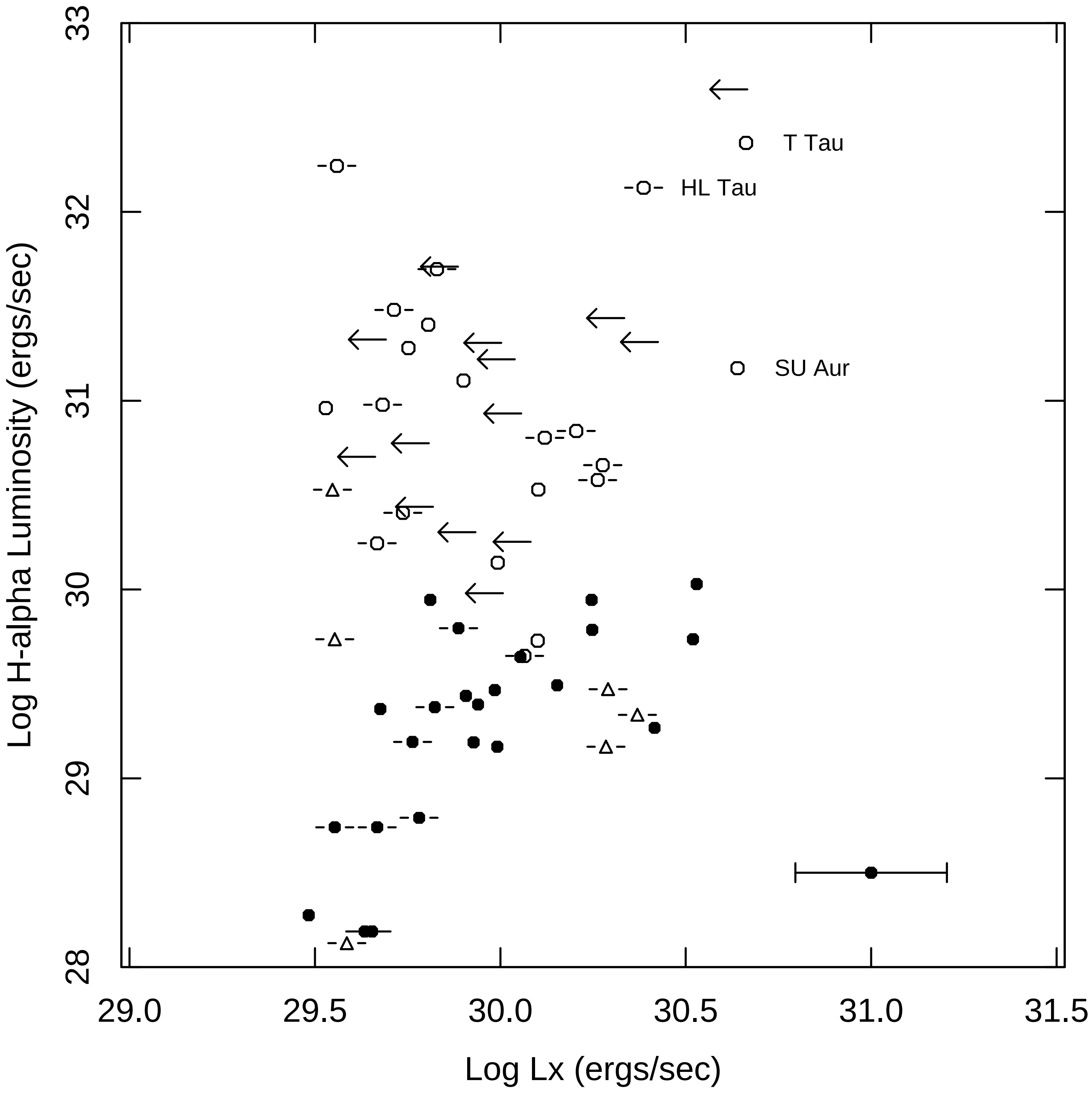
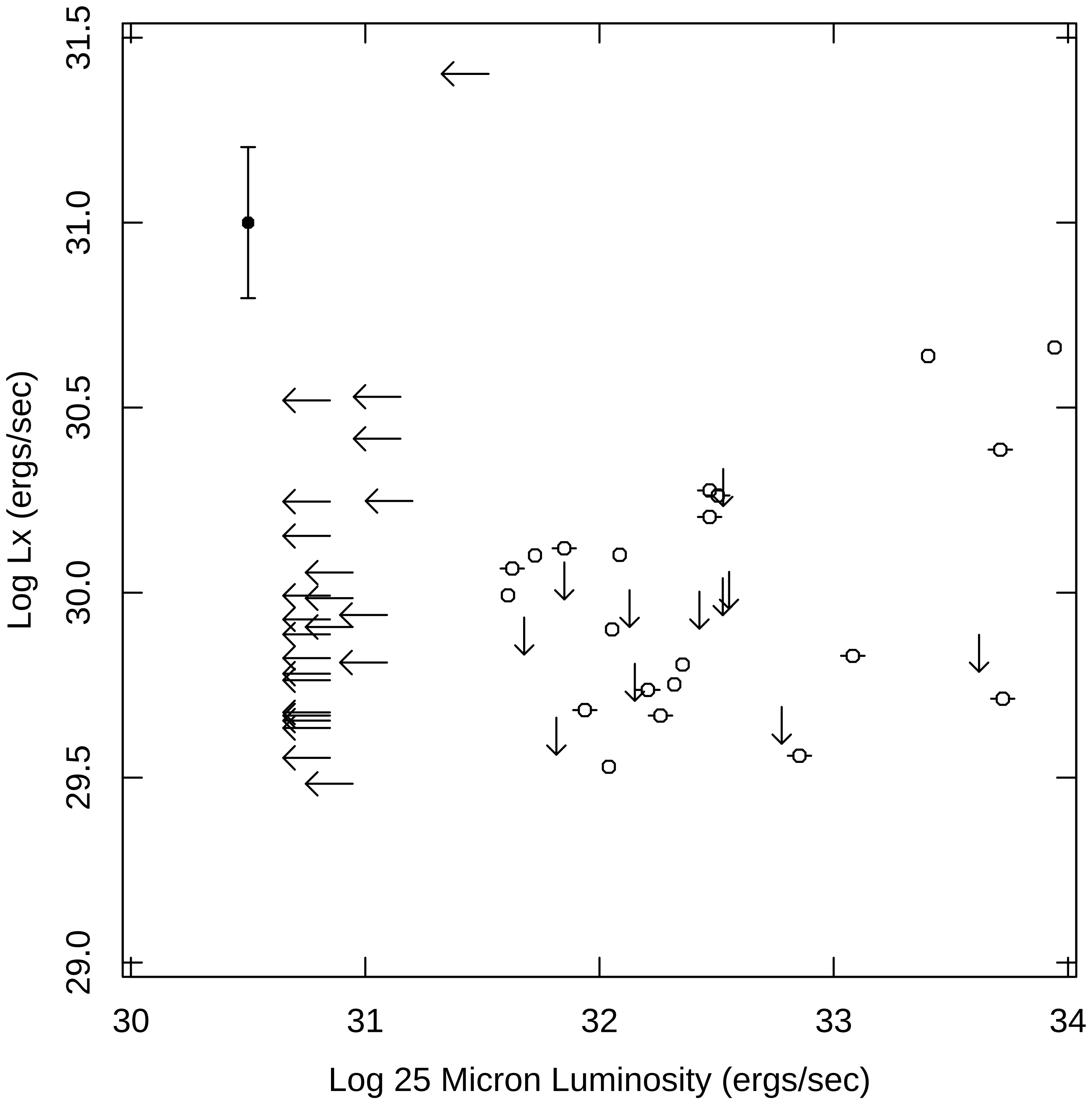

T Tau
HL Tau
SU Aur
Log H-alpha Luminosity (ergs/sec)
Log Lx (ergs/sec)
28
29
30
31
32
33
29.0
29.5
30.0
30.5
31.0
31.5

Figure 7



31.5
31.0
30.5
30.0
29.5
29.0
Log Lx (ergs/sec)
30
31
32
33
34
Log 25 Micron Luminosity (ergs/sec)

Figure 8

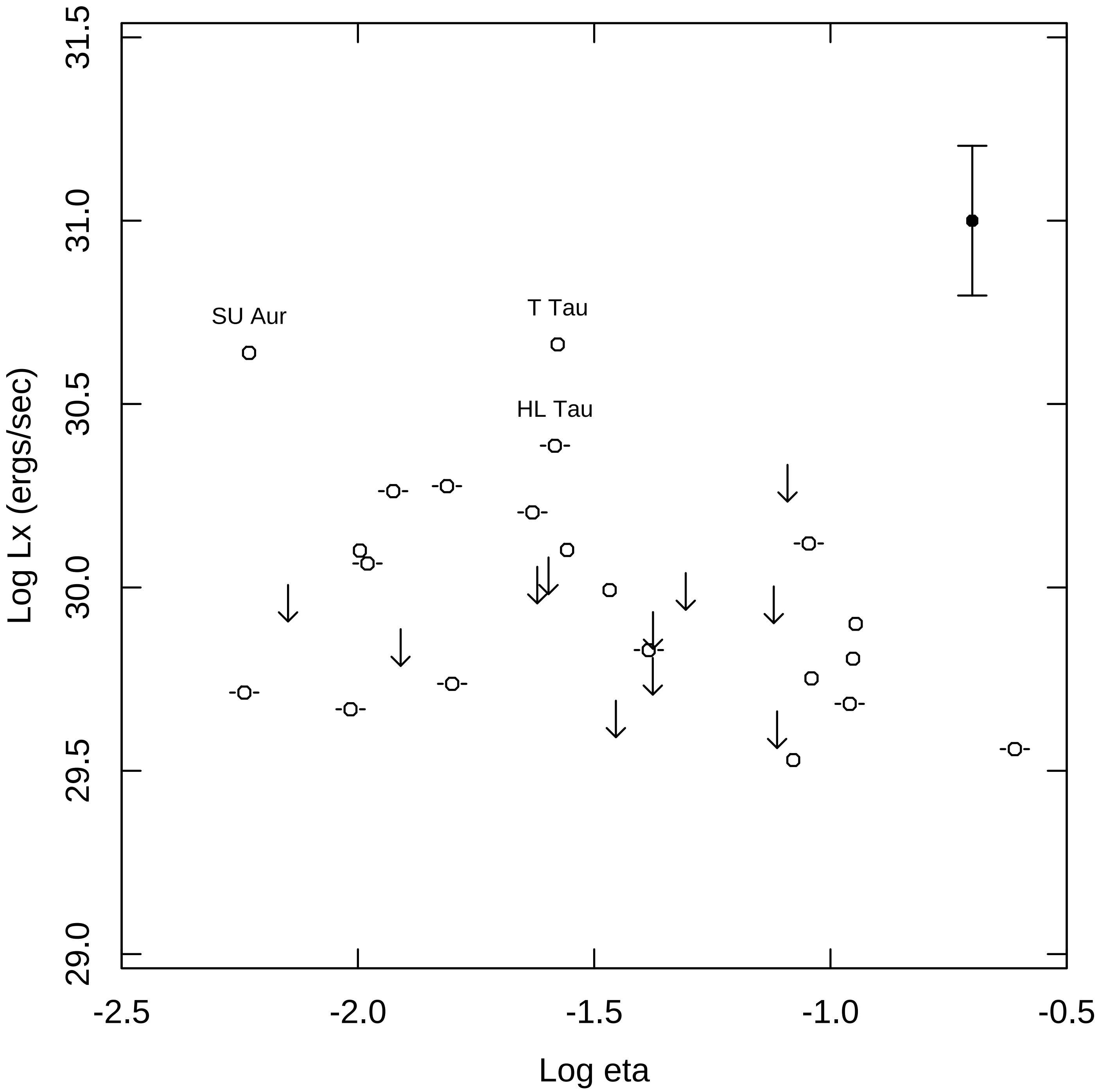
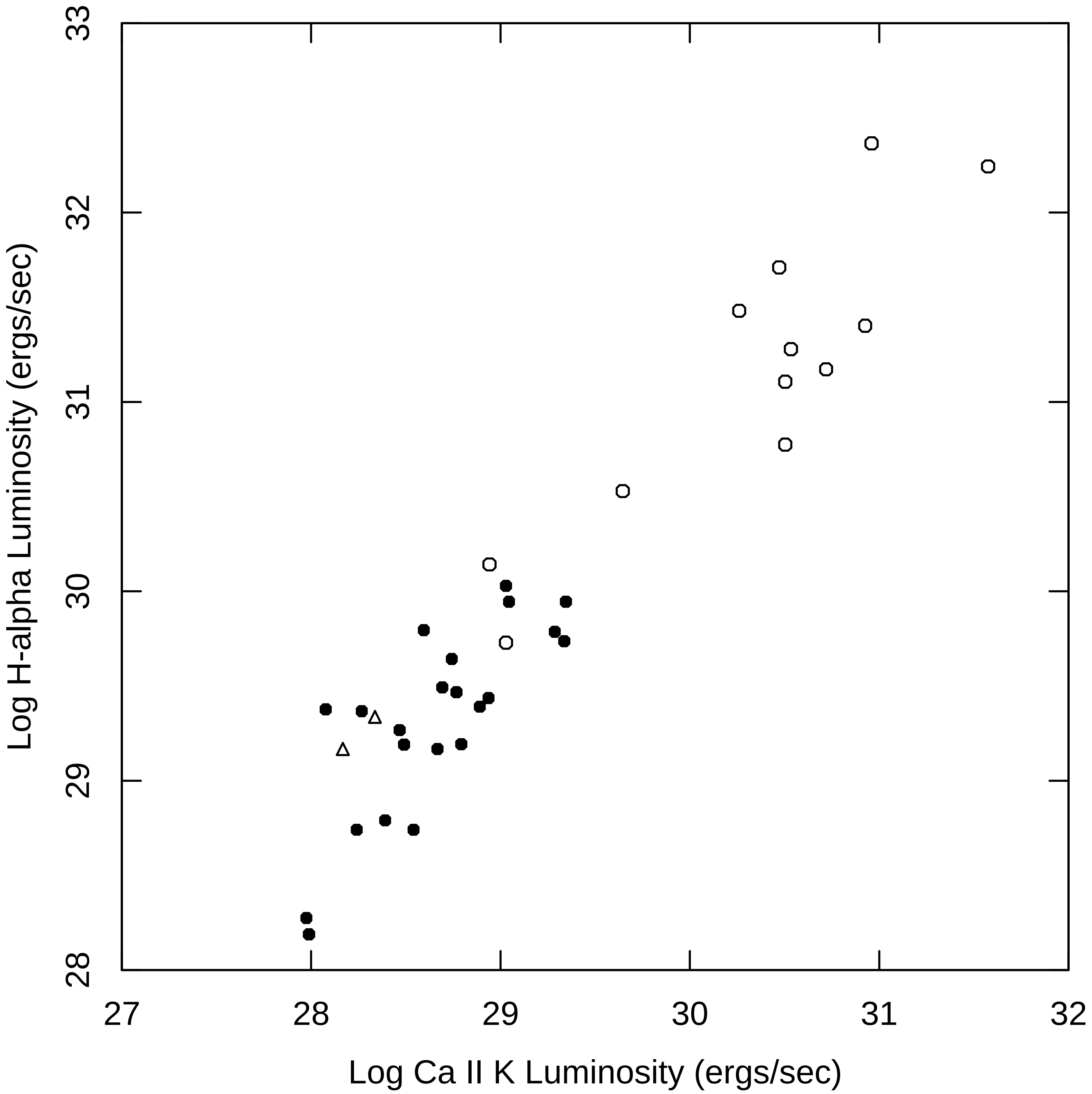
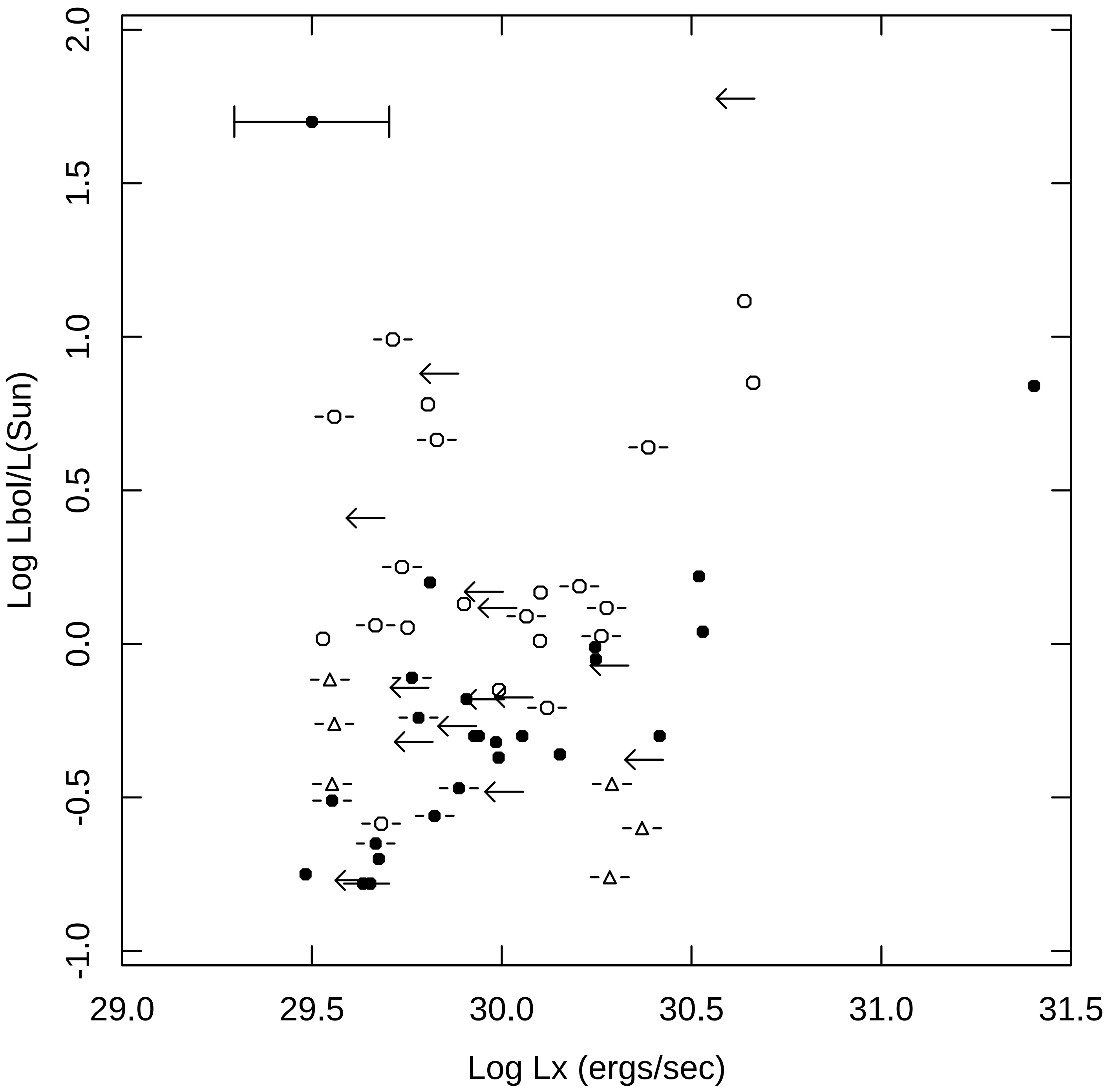

SU Aur
T Tau
HL Tau
31.5
31.0
30.5
30.0
29.5
29.0
Log Lx (ergs/sec)
-2.5
-2.0
-1.5
-1.0
-0.5
Log eta

Figure 9



Log H-alpha Luminosity (ergs/sec)
33
32
31
30
29
28
27
28
29
30
31
32
Log Ca II K Luminosity (ergs/sec)

Figure 10



Log Lbol/L(Sun)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
29.0
29.5
30.0
30.5
31.0
31.5
Log Lx (ergs/sec)