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A spectroscopic study of flares on T Tauri and zero-age main-sequence stars

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Abstract. Using a multi-object spectrograph on the Schmidt telescope in Tautenburg, we study the flare-activity of T Tauri stars and of zero-age main sequence stars. The sample comprises both classical, and weak-line T Tauri stars (cTTSs, wTTSs) in the Taurus-Auriga star forming region, as well as zero-age main-sequence stars (ZAMSSs) in the open cluster α Persei. The properties of the flares detected on V 486 Per in the α Persei region, and on the Weak-Line T Tauri stars V 819 Tau and V 410 Tau are rather similar: All events show a rapid increase and a slow decay of the strength of the Balmer lines, and all events have similar flux-ratios of Hγ to Hβ. An event which shares these properties has also been detected in the cTTS FN Tau, and we correspondingly interpret it as a magnetic flare. Using the properties of observed flares as criteria for the detection of such events, we study the frequency of flares in the three classes of objects. Using these criteria, we detected flares on 80% of the wTTSs, on 56% of the cTTSs, and on 16% of the ZAMSSs. We find that the intrinsic flare rate is only about a factor of two smaller for cTTSs than for wTTSs for our sample of stars, and for flares with energies $\geq 2\,10^{32}$ erg in Hβ. We thus conclude that a strong flare activity is a common property of both types of T Tauri stars. In contrast to the T Tauri stars, we find a drastically lower flare rate for the zero-age main sequence stars.

Key words: stars: flare – stars: formation – stars: pre-main sequence

1. Introduction

Classical T Tauri stars (henceforth called cTTSs) are young, low mass, optically visible pre-main sequence stars with accretion disks. Weak-Line T Tauri stars (henceforth called wTTSs) resemble the classical ones but lack disks, and accretion. It has been a mystery as to how the rotation rates of cTTSs are kept much lower than the breakup velocity, despite the large accretion rates, and despite the fact that cTTSs are still contracting towards the main sequence. Currently, the most favoured model is the magnetic accretion scenario in which a strong magnetic field couples to the star and the disk, so that angular momentum flows outward in the disk, while matter flows inward (Königl 1991; Cameron & Campbell 1993; Cameron et al. 1995; Armitage & Clarke 1996).

Although a few direct measurements of the field strength now exist (Guenther et al. 1999, Johns-Krull et al. 1999), the evidence that most, or all T Tauri stars have strong fields is still rather sparse. As discussed in more detail in Guenther et al. (1999), direct measurements of the field strength are rather difficult, and limited to very few T Tauri stars.

In principle, observations of flares might be used as indirect evidence for the presence of magnetic fields. Since these observations are not limited to certain stars, observations of flares could tell us how common magnetic activity is amongst young stars. Flare-like events have indeed been detected in cTTSs and wTTSs in X-rays. These events are so similar to flares on dMe stars that they are canonically interpreted as enhanced solar-type flares (Feigelson & DeCampi 1981; Walter & Kuhi 1984; Montmerle et al. 1993; Preibisch et al. 1993). While the discovery of X-ray flares on T Tauri stars is not surprising as all late type stars show flares (Schmitt 1994), the enormous energy-output of the events is impressive. The energy released in these flares in the 0.1–$2.4\,keV$-band are sometimes as large as $5\,10^{37}$ erg, compared to $6\,10^{34}$ erg for the largest flares of dMe stars (Hawley & Pettersen 1991). X-ray flares on T Tauri stars often last for several hours (Skinner at al. 1997; Preibisch et al. 1993). Using a scaled-up model of a solar flare, and the observed temperatures and decay times, Preibisch et al. (1993) were able to derive a lower limit of the magnetic flux density of 210 G, and an emitting volume of $2\,10^{33}\,\mathrm{cm}^3$, implying that very strong magnetic fields must indeed be present. Observations of the very rapidly rotating zero-age main-sequence star (henceforth called ZAMSS) AB Dor (age $10^6 - 3\,10^7$ years) implies that the X-ray flares are indeed connected to large star-spots (Vilhu et al. 1993).

Flares not only emit X-rays but all kinds of electromagnetic waves, from γ-rays down to radio waves (Somov 1992). Recent simultaneous optical and X-ray observations of a solar flare show that the light curves of $H\beta$ and soft X-rays (0.25–4.0 keV) are almost identical, implying that the Balmer-lines are probably induced during a flare by the soft X-ray radiation (Johns-Krull et al. 1997a). Although the optical emission is a secondary effect,

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it is a necessary ingredient of a flare, and if the interpretation of X-ray data is correct, optical flaring must be observable.

After the pioneering work of Haro & Chavaria (1965) it has been well established that young stars have optical flares. Since rapid increases of the brightness in the optical regime and variations of spectral lines on time scales of less than an hour have occasionally been observed in T Tauri stars too (e.g. Bastian & Mundt 1979), the picture seems, at first sight, to be rather consistent.

However, a statistical analysis of broad-band photometry of T Tauri stars by Gahm (1990) indicates that while the colours and the light curves of events on wTTSs were flare-like, the events on cTTSs were not. Gahm correspondingly interprets the events observed on cTTSs as variations of the extinction, or variations of the veiling continuum but not as flares. This conclusion is further supported by a simultaneous spectroscopic and photometric monitoring of two cTTSs and three wTTSs by Gahm et al. (1995). Although three flares on wTTSs were found, no flare was observed in a cTTS. Unfortunately, the only attempt to observe a cTTS (BP Tau) simultaneously in the optical and in X-rays was unsuccessful, as no optical data were taken at the moment when an X-ray flare occurred (Gullbring et al. 1997). A small optical variation had no counterpart in the X-rays. That means that either X-ray flares on cTTSs have no optical counterparts, or have just been missed by chance. Given the low frequency of X-ray flares of about $0.01\,\mathrm{h}^{-1}$ (Gahm 1990) this seems plausible. The question, whether cTTSs have optical flares or not thus remains unsolved.

Flares are not only important as indirect evidence for the presence of magnetic fields in young stars but might be important for ionizing the circumstellar disk. This is because flares lead to an increased X-ray flux, harden the X-ray spectrum, and increase the flux of high energy particles (Glassgold et al. 1997; Tsuboi et al. 1998). Although the flare-activity declines with age, flares could also be important in the later stages of the evolution, because the EUV and X-ray emission of the young Sun might have been important for the formation of a planetary ionosphere (Güdel et al. 1997).

Progress in optical studies of flares from young stars was hitherto severely hindered by the rarity of the events. However, the multi-object spectrographs now allow to study many T Tauri stars simultaneously, thereby increasing the probability for detecting such events enormously. We thus have started a monitoring campaign to search for flares using the UK Schmidt telescope in Siding Springs and the Schmidt telescope in Tautenburg. On the basis of the data taken in our first observing run on the UK Schmidt telescope, we demonstrated that flares can be studied very efficiently using such an instrument, and we have reported on the detection of two flares in wTTSs (Guenther & Emerson 1997, henceforth called paper I). However, up to now, no flares were detected in cTTSs.

The first aim of this paper is to report on a possible detection of a flare in the cTTS FN Tau. In order to discuss whether this event was a flare or not, we compare it with a flare in a ZAMSS, and with three flares observed in wTTSs which were observed with the same equipment. Since wTTSs and ZAMSSs are known to show flare activity, these events serve as typical examples for flares observed spectroscopically on young stars.

The second aim of the paper is to study the frequency of flares in the three groups of stars. For that purpose, we use the properties of these flares to define criteria for the (semi)-automatic detection of flares in our time series of 7674 spectra.

2. Observations and data-reduction

For our observations we use the multi-object spectrograph TAUMOK (Lehmann et al. 1995) on the 134/200 cm Schmidt telescope in Tautenburg. TAUMOK is equipped with 36 steel rods that can be positioned by a robot within a $2\overset{\circ}{.}3$ circular field of view. In total, the rods carry 52 $100\mu\mathrm{m}$ fibres (corresponding to $5\overset{\prime\prime}{.}0$ as projected onto the sky). For this study, we selected a sample of 9 cTTSs and 10 wTTS in the Taurus-Auriga star forming region (see Table 2, and Table 3). Additionally, we observed 23 late type stars in the α Persei cluster ($B-V \geq 0.58$ mag), spanning the entire range of $\mathrm{v}\sin\mathrm{i}$ from 10 to 205 $\mathrm{km\,s^{-1}}$. Five fibres were placed on non-variable stars in the case of the Taurus-Auriga field, and ten in the case of the α Persei region. These non-variable stars served as secondary flux standard stars. The remaining fibres were used to measure the sky-background. Exposure times ranged from 600 to 1200 seconds, depending on the weather conditions. In total, we took 2088 spectra of cTTSs, 2320 spectra of wTTSs, and 3266 spectra of ZAMSSs. The Taurus-Auriga field was monitored for 45 hours, and the α Persei cluster for 30 hours.

After the field has been initially acquired, each fibre was individually repositioned to maximise the throughput. The fibres were also repositioned whenever the differential atmospheric refraction became larger than $1\overset{\prime\prime}{.}5$. Because of the repositioning feature of the instrument, the stars were always kept quite close the centre of the fibre, thus making a flux calibration possible by using the none-variable stars that were observed simultaneously. We derived the absolute fluxes of these secondary flux standards by observing our Taurus and our α Persei fields, and the flux-standard $\mathrm{BD}+25^\circ\,4655$ at different airmasses in a photometric night, and by using an extinction model which was derived from these observations. The relative throughput for each fibre was calibrated by using dawn-flats. However, since α Persei passes close to the zenith in Tautenburg, the photometric accuracy is much higher for the Perseus field than for Taurus field.

It turned out that the photometric accuracy was high enough for the α Perseus region, to allow searching for flares as variations of line, and continuum flux. In contrast to this, the photometric errors the B and V-band in the Taurus region were often as large as 0.6 mag, since Taurus could only be observed at larger air-masses. In this region, we had to rely on EW measurements to identify flares.

Because of the large $H\alpha$ emission line in the cTTSs, flares are probably more difficult to detect in this line than in the other Balmer lines. We thus observed the wavelength range from 3600 to 6100 Å, which covers the higher Balmer lines including Hβ and Hγ. The dispersion of the spectra is about 2.4 Å per pixel. Standard IRAF routines were used to subtract the bias, to remove

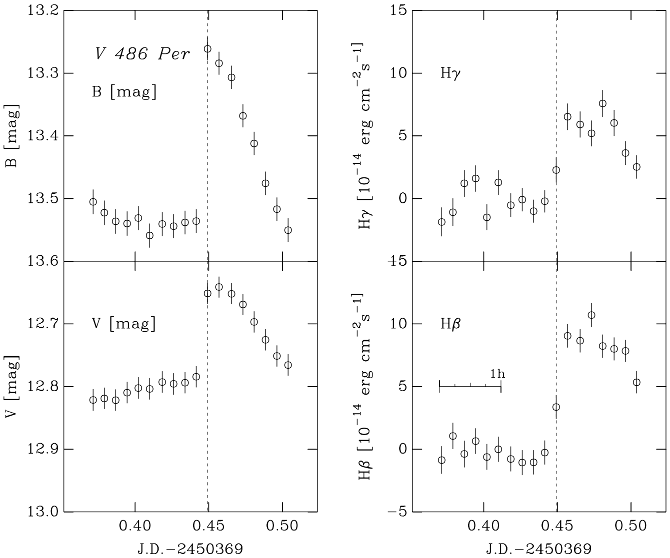

Fig. 1. A flare in V 486 Per on J.D. 2450369. Shown on the left side are the brightness of the star in the V and B-band, and on the right the flux variation in the $H\beta$ and Hγ. The flare is seen in both broad-band colours and in both lines. Since only the relative increase of the line is of interest, the pre-flare level of the equivalent width was set to zero. The event clearly shows the properties of a flare, as the brightness of the star increases rapidly, and declines slowly. A rapid increase and slow decay of the fluxes in $H\beta$ and Hγ is also visible. Compared to the broad-band colours, the increase and the decline is slower in the spectral lines.

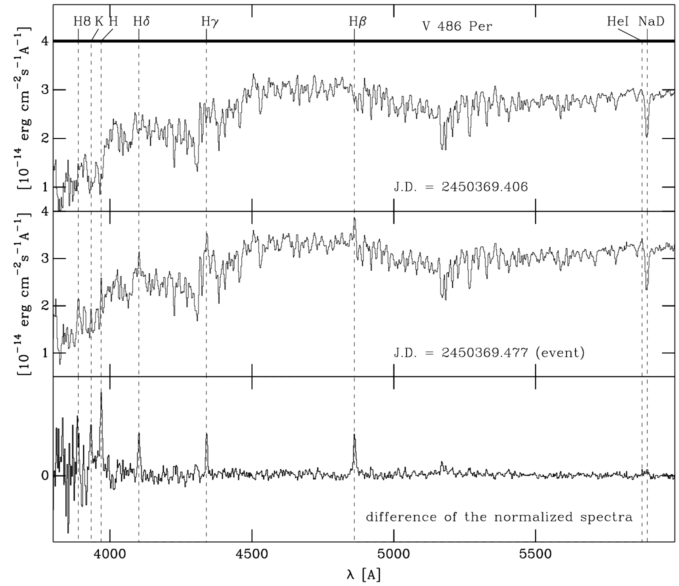

Fig. 2. Averaged, flux-calibrated spectra of V 486 Per before (*upper panel*) and during (*middle*) the flare. The *lowest panel* shows the difference between the two spectra after normalising to the same continuum. Clearly visible is that the fluxes of Hβ Hγ, Hδ, and the $\mathrm{Ca\,II\,H}$ (+Hϵ) and $\mathrm{Ca\,II\,K}$ lines increased too during the event.

the scattered light, and to wavelength-calibrate the spectra. The sky background was removed by subtracting the averaged output of all fibres that were placed on the sky-background, after the relative throughput for each fibre had been corrected.

3. Results

3.1. Individual events

3.1.1. A flare in the ZAMSS V 486 Per

V 486 Per (=AP 43) is known as a a chromospherically active BY Draconis star in the α Persei open cluster (Kholopov et al. 1987; Randich et al. 1996). The colour index (B-V=0.97) implies a spectral type of K3V. V 486 Per is quite a fast rotator ($\mathrm{v}\sin\mathrm{i} = 72\,\mathrm{km\,s^{-1}}$), and is relatively bright in soft X-rays $(0.98 \pm 0.07)\,10^{30}\,\mathrm{erg\,s^{-1}}$ (Randich et al. 1996). Stauffer et al. (1985) discovered a periodic variation of the brightness of the star with an amplitude of 0.1 mag. The period is 13.495 h. The most likely explanation for this variation is the presence of a large spot.

Fig. 1 shows the light-curve in the B and V-band, and the fluxes of Hβ and Hγ on J.D.2450369. An event which is characterised by a rapid rise of the fluxes measured in the broad-band colours, as well as in Hβ and Hγ is clearly visible. The increase of the flux measured in the broad-band colours took less than 700 s, compared to about 1400 s in Hβ and Hγ. The decay times from maximum to half-peak luminosity in B and V ($\mathrm{t_{0.5}(B,V)}$) were 2600 s and 3100 s, respectively. Since the increase of the fluxes of the Balmer lines was much larger than the increase of the continuum, the equivalent width of the lines changed during the event as well. The general shape of the curve of the equivalent width is identical in Hβ and Hγ. At the end of the observations, the Hβ flux was still larger than half of the peak intensity. We crudely estimate $\mathrm{t_{0.5}}$ to be about 8000 s for Hβ and about 4000 s for Hγ. Although the estimates for the decay time of the lines are very rough, we conclude that the rise as well as the fall was much slower in the lines than in the continuum.

Fig. 2 shows the average spectra before, and during the event. The third spectrum is the difference between the averaged spectra in the two states, after the continuum of the spectra has been normalised. From the spectrum of the difference, we conclude that fluxes of Hβ, Hγ, Hδ, and the $\mathrm{Ca\,II\,H}$ (+Hϵ) and $\mathrm{Ca\,II\,K}$ lines increased during the event. The total released energy in the spectral lines after dereddening, the rise and decay times, and the ratio of the fluxes between Hβ and Hγ after subtracting the fluxes in quiescence are given in Table 1.

This star shows the high chromospheric activity which is typical for BY Draconis stars. Hence, the observation of a flare in this star is not surprising. The properties of the event represent in every respect what can be expected for a flare. Since ZAMSSs do not accrete matter, we are certain that this event was a flare. Since the relative change of the flux in the lines is much larger than the relative change of the continuum, the equivalent widths of lines increased during the event. The flare thus could also have been detected from the variations of the equivalent width alone. This property of flares is well known, and will be used for the stars in Taurus. The ratio of the fluxes in Hβ to Hγ during the event is 0.69. For flares on the Sun, this ratio is between 0.38

Table 1. Released energies, and increase and decay times of the individual events

type	star	total energy released [10^{33}erg][1] $H\beta$	$H\gamma$	$H\delta$	Ca II H +Hϵ	$t_{rise}(H\beta)^2$ [s]	$t_{0.5}(H\beta)^3$ [s]	$\frac{\Delta E(H\beta)}{\Delta E(H\gamma)}$
ZAMSS	V486 Per	$> 2.43 \pm 0.33$	$> 1.67 \pm 0.34$	$> 1.69 \pm 0.60$	$> 3.28 \pm 1.01$	1300	> 5400	0.69
wTTS	V819 Tau	0.67 ± 1.13	-	-	-	≤ 700	1500	0.48
wTTS	V819 Tau	$> 7.90 \pm 2.24$	$> 5.30 \pm 2.69$	$> 2.40 \pm 2.50$	$> 9.28 \pm 4.15$	1300	4700	0.67
wTTS	V 410 Tau	$> 2.10 \pm 1.45$	$> 1.85 \pm 1.00$	$> 0.64 \pm 0.44$	$> 1.00 \pm 0.56$	2700	3000	0.88
cTTS	FN Tau	5.06 ± 2.29	4.53 ± 2.12	2.93 ± 2.49	5.60 ± 3.74	1900	1800–2100	0.90

[1] For some events, the total energy released is a lower limit, because the observations ended before the end of the flare.
[2] the rise time from the quiescent level to the peak in $H\beta$
[3] the decay time from maximum to half-peak luminosity

and 0.57 (Johns-Krull et al. 1997a), and for flares on AD Leo between 0.77 and 0.83 (Hawley & Pettersen 1991). The flux ratio of Hβ to Hγ for this flare is thus in the middle between the two.

3.1.2. Two flares on the wTTS V 819 Tau

V 819 Tau is a wTTS. The equivalent width of the $H\alpha$ is 4 Å, the spectral type is K7 V and a $\mathrm{v}\sin\mathrm{i} < 15\,\mathrm{kms}^{-1}$ (Herbig & Bell 1988). This star is known to show quasi-periodic variations with a period of 5.5 days, and an amplitude of 0.3 mag. These variations can be interpreted as being due to the presence of a very large star-spot. Flares, or any other short-time variability has not been reported previously (Rydgren & Vrba 1983; Grankin et al. 1995; Grankin 1997). V 819 Tau has also been detected as an X-ray source by ROSAT. The flux in X-rays is $L_x = (0.88 \pm 0.13)\,10^{30}\,\mathrm{erg\,s}^{-1}$ (Wichmann et al. 1996). A massive disk does not seem to be present, as the star has not been detected at 1.2 mm (Osterloh & Beckwith 1995).

Fig. 3 shows the curves of the equivalent widths for Hβ and Hγ on J.D.2450423. In this night we observed the field continuously for 8.1 hours and took 43 spectra of this star. Clearly visible are two (maybe even three) events in both lines. Both events are characterised by a rapid increase and slow decrease of the equivalent width. The general shape of the curve is identical in the two lines. For the first event, the rise-time was less than 700 s in Hβ, and the decay-time $t_{0.5}(H\beta) \sim 1500$ s. For the second event, we measure a rise-time of $t_{rise}(H\beta) \sim 1300$ s and a decay-time $t_{0.5}(H\beta) \sim 4700$ s. Table 1 lists the energies released in the lines.

As mentioned before, the events are detected from the change of the equivalent width not the line-fluxes. Significant increases of the equivalent width have been detected for all lines listed in Table 1. However, problems of the calibration of the absolute fluxes often caused large errors for the amount *of energy released*. Thus, this value is not well determined. Contrary to this, the ratio of the fluxes of Hβ to Hγ is well determined, because it is measured in the same spectrum and does not depend on the determination of the absolute fluxes.

Fig. 4 shows the average spectrum of the second event, the spectrum of the quiescent state, and the difference between the

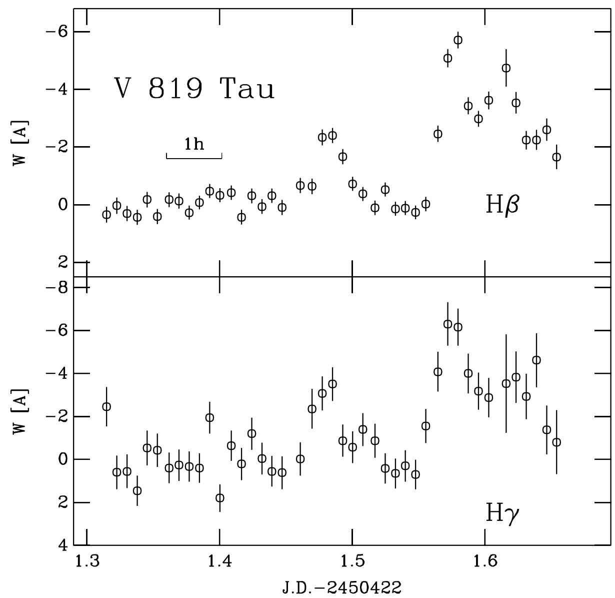

Fig. 3. Variations of the equivalent widths in Hγ and Hβ of the wTTS V 819 Tau on J.D. 2450423. The pre-flare level is of the equivalent width is set to zero. Two, maybe three events are visible in both lines. In both events, the rise is faster than the fall. Since only the relative increase of the equivalent width is of interest, the pre-flare level of the line was set to zero.

two. From these spectra, we conclude that Hβ, Hγ, Hδ and Ca II K were enhanced during the event. The blend consisting of Ca II H and Hϵ was also enhanced. The flux ratios of Hβ to Hγ are again quite similar to AD Leo (Hawley & Pettersen 1991), and V 486 Per (Table 1). Although the photometric accuracy is low, by using all frames taken during the flare-event, we were able to derive reasonably accurate values for the total energies released (Table 1).

The properties of the two (maybe even three) events have the same characteristics as the flare in V 486 Per in every respect, and we thus interpret these events as two flares. Also, the star has a very large spot, and thus the observation of flare is very plausible. We also note that multiple flares within a short time are common for flares on the sun (Zirin **?**), and on flares stars (Hawley et al. 1995).

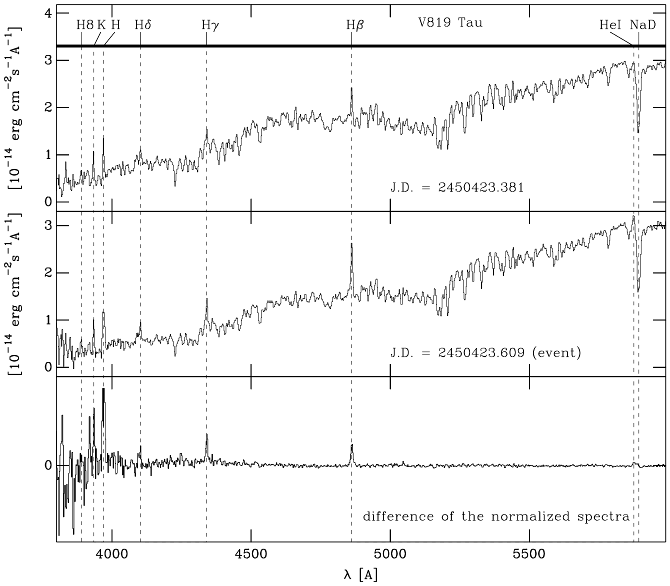

Fig. 4. Averaged, and flux-calibrated spectra of the wTTS V 819 Tau before (*upper panel*) and during (*middle*) the event observed. The *lowest panel* shows the difference between the two spectra after normalising to the same continuum. We conclude that the flux of Hβ, Hγ, Hδ, and the $\mathrm{Ca\,II}$ H(+Hϵ) and $\mathrm{Ca\,II}$, K increased during the event.

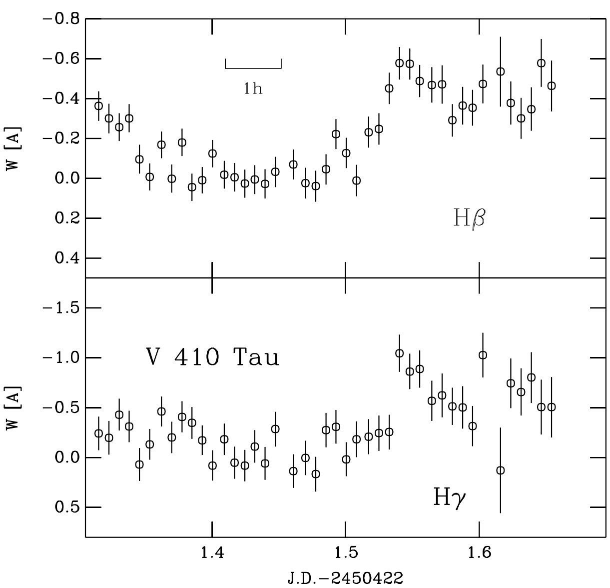

Fig. 5. Variations of the equivalent width of the wTTS V 410 Tau in Hγ and Hβ. The pre-flare level of the equivalent width is set to zero. A rather slow event seems to have happened in the second half of the night.

3.1.3. A flare in wTTS V 410 Tau

V 410 Tau is one of the most active wTTSs known. Doppler imaging reconstructions of the surface features shows the presence of a large, cool polar spot (Joncour et al. 1994; Strassmeier et al. 1994; Hatzes 1995; Rice & Strassmeier 1996). Broad-band photometry implies that this spot is older than 6 years (Petrov et al. 1994). Recently, Donati et al. (1997) detected a magnetic

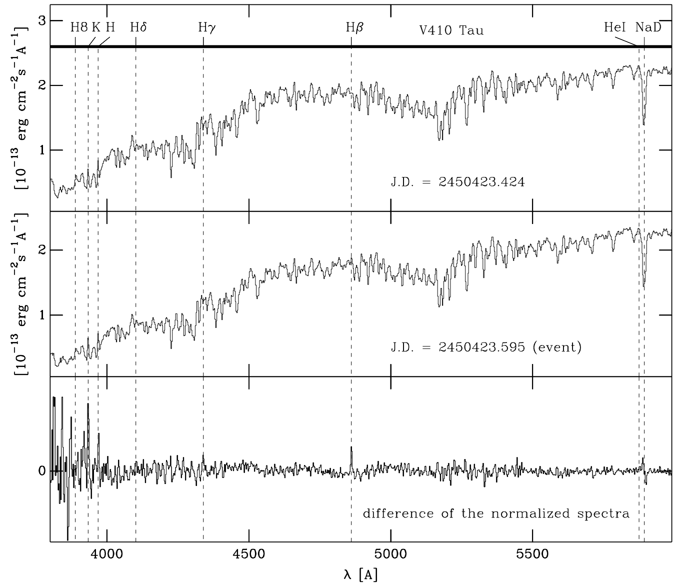

Fig. 6. Averaged, and flux-calibrated spectra of the wTTS V 410 Tau before (*upper panel*) and during (*middle*) the event observed. The *lowest panel* shows the difference between the two spectra after normalising to the same continuum. From this spectrum, we conclude that the flux of Hβ, Hγ, and the $\mathrm{Ca\,II\,H}$ (+Hϵ) and $\mathrm{Ca\,II\,K}$ increased too during the event.

field using spectro-polarimetric methods. With a rotation period of 1.872095 ± 0.000022 days (Petrov et al. 1994), and $\mathrm{v}\sin\mathrm{i}$ of $73\,\mathrm{km\,s^{-1}}$ (Herbig & Bell 1988), V 410 Tau is also one of the most rapidly rotating wTTSs known. The equivalent width of $H\alpha$ is 3 Å, the spectral type K3V (Herbig & Bell 1988). V 410 Tau was also detected with ROSAT. The brightness in X-rays is $L_x = (2.6 \pm 0.3)\,10^{30}\,erg\,s^{-1}$ (Wichmann et al. 1996). The radio emission of V 410 Tau is highly variable, and the radio spectrum is non-thermal (Bieging et al. 1984). No disk seems to be present as the star has not been detected at 1.2 mm (Beckwith et al. 1990).

Fig. 5 shows a small event which was clearly visible in Hβ but was only marginally detected in Hγ. With a measured rise time $\mathrm{t_{rise}(H\beta)}$ of about 2700 s, this event is much slower than the events in V 486 Per and V 819 Tau. The determination of the decay-time is very inaccurate, because of the large scatter of the points at the end of the night. We estimate $\mathrm{t_{0.5}(H\beta)} \sim 3000$ s. Although Hγ shows the same trend, the increase in equivalent is relatively small. The lower panel of Fig. 6 shows differences between the average spectrum before and during the event. Apart from Hβ, and Hγ, the event is only visible in the $\mathrm{Ca\,II\,H}$ (+ Hϵ) and $\mathrm{Ca\,II\,K}$ lines.

The rise time $\mathrm{t_{rise}(H\beta)}$ for this event is clearly much longer than that of the other events. Spectroscopy of V 410 Tau by Fernández & Miranda (1994) shows that the strength of the $H\alpha$ line varies with the rotation period of the star. The equivalent width increases, if a more active region comes into view. However, the rise-time due to this effect (measured from the minimum to the maximum) is about 20000 s, much longer than the 2700 s we measured for this event. It thus seems unlikely

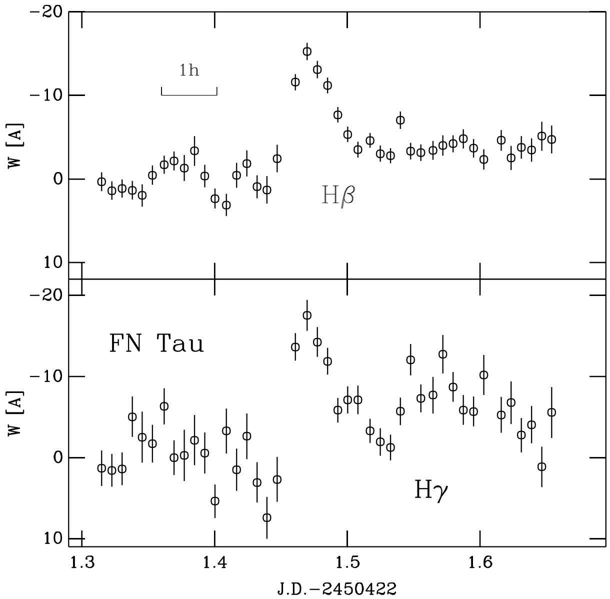

Fig. 7. Variations of the equivalent width of of the cTTS FN Tau in Hγ and Hβ. The pre-flare level of the equivalent width is set to zero. Clearly visible is a flare-like event in both lines.

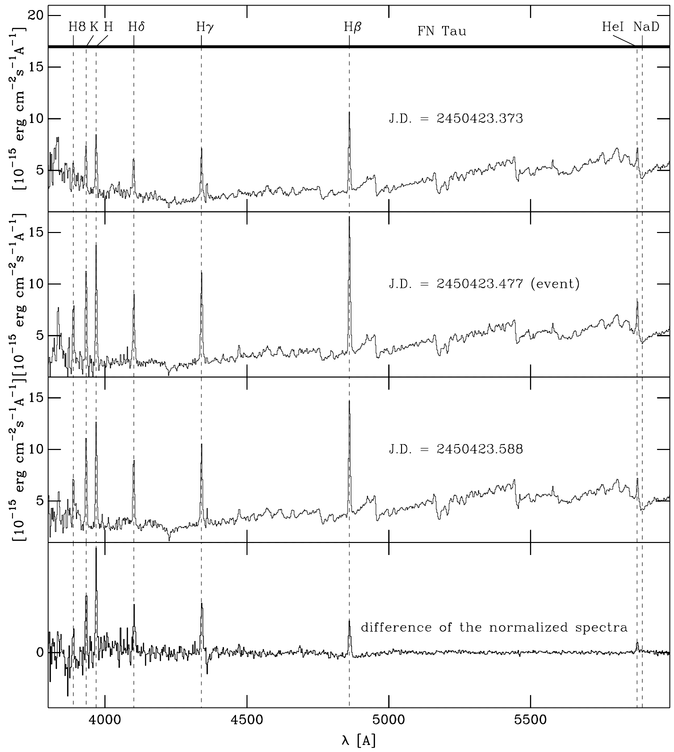

Fig. 8. From *top* to *bottom:* Averaged, and flux-calibrated spectra of the cTTS FN Tau before, during and after the event observed. The *lowest panel* shows the difference between the quiescent and the active state. The Hβ, Hγ, Hδ, $H8$ and the $\mathrm{Ca\,II\,H}$ (+ Hϵ) and $\mathrm{Ca\,II\,K}$ lines are clearly visible in the spectrum of the difference, indicating that these lines must have increased during the event.

that the observed increase of the equivalent width of Hβ is due to an active region rotating into view. The most likely explanation for this event again is a flare. Although the relative increase of equivalent width is much smaller than for the other events, the energy released (Table 1) is comparable, because V 410 Tau is much brighter in the continuum.

3.1.4. The event in the cTTS FN Tau

FN Tau is a cTTS with an equivalent widths of 24.7 Å and 13.1 Å in $H\alpha$, and Hβ, respectively. The presence of a disk is inferred from the relatively large brightness observed at 1.2 mm (Beckwith et al. 1990). The spectral type of this stars is M5V, and the extinction $A_v = 1.40 \pm 0.04$ (Cohen & Kuhi 1979). FN Tau has not been detected with ROSAT. The upper limit is $L_x < 0.37\,10^{30}\,erg\,s^{-1}$ (Wichmann et al. 1996). A flare, or a flare-like variation has not yet been observed in the optical, or in the X-rays.

Fig. 7 shows the variations of the equivalent widths of Hβ and Hγ on J.D. 2450423. Clearly visible is a large event in the middle of the night. This event is again characterised by a rapid increase and slow decay of the equivalent width of Hβ and Hγ. The upper limit for an increase in the flux in the B, and V-band is 0.40 and 0.38 mag. However, the equivalent widths do not go back to the pre-flare level after the event. Spectra taken on the following night still have the same equivalent widths as directly after the event. The measured rise-time for Hβ is about 1900 s. The decay-time, depending whether the increase of the quiescent level is taken into account or not, is $\mathrm{t}_{0.5}(\mathrm{H}\beta) = 1800\,\mathrm{s}$, or 2100 s. Fig. 8 shows the averaged spectra before, during, and after the event, as well as the spectrum of the difference between the quiescent and the event state. The spectrum of the difference clearly shows that Hβ, Hγ, Hδ, $\mathrm{Ca\,II\,K}$, $\mathrm{He\,I\,5876}$, and the blend consisting of $\mathrm{Ca\,II\,H}$ and Hϵ, indicating that these lines were enhanced during the event. The ratio of the fluxes of Hβ to Hγ is again quite similar to that of AD Leo (Hawley & Pettersen 1991; Table 1).

3.1.5. Interpretation of the event observed in FN Tau

The ratios of $\mathrm{t}_{\mathrm{rise}}(\mathrm{H}\beta)$ to $\mathrm{t}_{0.5}(\mathrm{H}\beta)$ for FN Tau of about one. Since $\mathrm{t}_{0.5}(\mathrm{H}\beta)$ is the decay to half the intensity of the lines before the flare, the rise is at least a factor 2 faster than the decay. For the wTTSs V 819 Tau and V 410 Tau, and the ZAMSS V 486 Per we find values of $\mathrm{t}_{\mathrm{rise}}(\mathrm{H}\beta)\ /\ t_{0.5}(H\beta) > 2$, ~ 4, ~ 1, and > 4. Thus the event on FN Tau is at the slow end of what we observed for the other stars. The absolute value of the rise-time is comparable to that of the wTTSs. Additionally, we observed an enhancement of the same lines in FN Tau as in V 819 Tau, V 410 Tau, and V 486 Per. The enhancement of the $\mathrm{He\,I\,5876}$-line during the event clearly indicates the presence of regions with temperatures above 10000 K. The asymmetry of the curve in Fig. 7, and the time-scale of the event rule out any effect due to occultion or rotation.

Apart from a flare, the only other possible explanation is a sudden change of the accretion rate. Previous studies show that changes of the accretion rate are always accompanished

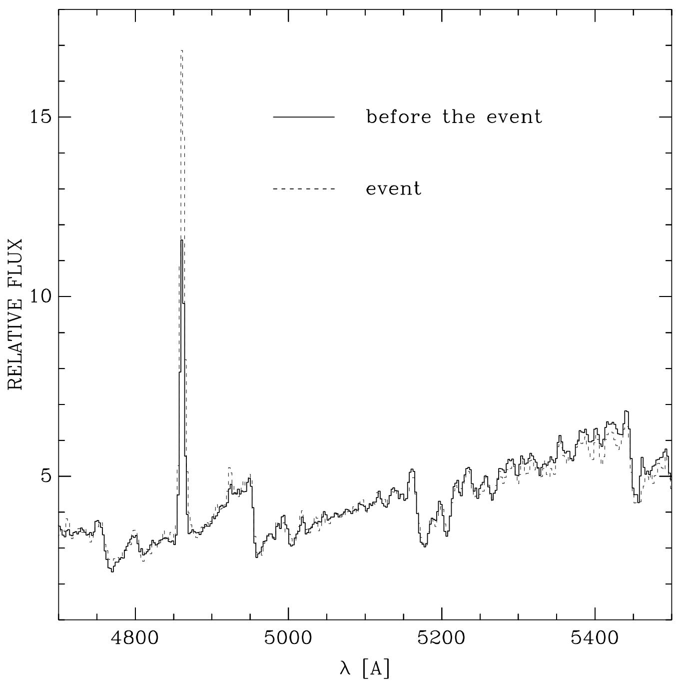

Fig. 9. Scaled up version of a part of the spectra shown in Fig. 8. Dashed line: the spectrum during the event. Full line: the spectrum before the event. If the event was due to a variation of the accretion rate, we would expect changes of the veiling, or changes of the profile of Hβ. The only noticeable difference of the two spectra is the strength of Hβ.

by variations of the veiling, and variations of the line profiles (Guenther & Hessman 1993; Hessman & Guenther 1997; Johns-Krull & Basri 1997b). For example, the appearance of an inverse P-Cygni absorption component during the event would be a definite sign for a change of the accretion rate. Fig. 9 shows a scaled-up version of the spectra taken before and during the event. Clearly visible are the Ti O band heads of the photospheric spectrum, and Hβ. Since the emission and absorption components of an inverse P-Cygni profile are typically separated by 100–300 $\mathrm{km\,s^{-1}}$ (Bonnell et al. 1998), they would be resolved in our spectra. Since we do not see any indication for variations of the veiling of the photospheric spectrum, nor any changes of the line profile in Hβ, the most likely explanation for this event is a flare.

3.2. The statistics of flares

In the previous section we have shown examples for flares in two wTTSs and in a ZAMSS. Additionally, we have presented observations of an event in the cTTS FN Tau with the same properties as those seen in the wTTSs and in the ZAMSSs, and which we correspondingly interpret as a flare. In this section we will use the common properties of these flares to derive general criteria for a semi-automatic detection of such events. These data will then be used to study the frequency of flares in the three classes of objects.

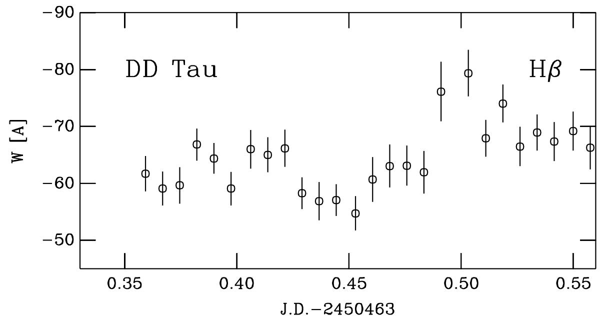

Fig. 10. Distinguishing flares from other changes of the equivalent width is often difficult. This is especially true for the cTTSs which occasionally show erratic variations of the equivalent width. Shown here is the variation of the equivalent width observed in DD Tau. Because the increase is faster than the decrease, we interpret this event as a weak flare.

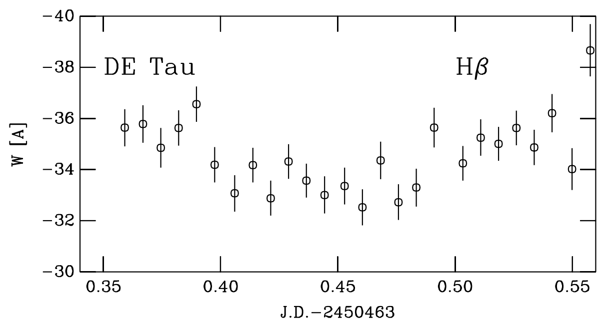

Fig. 11. Classical T Tauri stars occasionally show erratic variations of the equivalent which are difficult to distinguish from flares. As an example for such a behaviour, we show the variations of the cTTS DE Tau which we do not interpret as a sign of flare-activity.

3.2.1. Detection criteria for flares in a time series of spectra

As described in Sect. 3.1.1, flares can be detected by analyzing the variations of equivalent widths of $H\beta$ and $H\gamma$. Flares are characterised by a rapid increase, and slow decay. The first criterium thus is $\mathrm{t_{rise}(H\beta)} \leq \mathrm{t_{0.5}(H\beta)}$. Since $\mathrm{t_{0.5}(H\beta)}$ is the time in which the equivalent width goes back to half of the pre-flare value, this criterium means that the decay-time has to be larger than the rise-time by a factor of two.

The second criterium is that the increase of the equivalent width of Hβ has to be larger than 3 σ of the noise level. Since T Tauri stars often show very little variations in quiescence (see paper I), the noise-level is estimated from the scatter of the data-points in quiescence.

However, erratic variations of the strength of the equivalent width do occasionally occur in cTTSs, and it is sometimes quite difficult to distinguish these variations from flares. As an example for this problem we show the variations of the equivalent width of the cTTSs DD Tau (Fig. 10), and DE Tau (Fig. 11). In the case of DD Tau, we interpret the event in the second half of the night as a flare, because the rise seems to be faster than the decay. In contrast to this, the variations of the equivalent width in DE Tau does not seem to be flare-like.

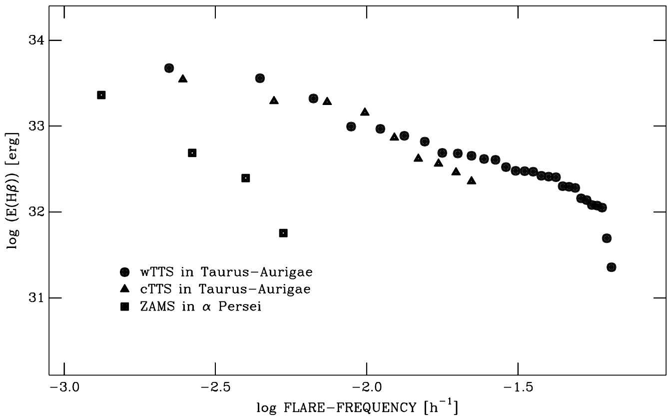

Fig. 12. Using the criteria described in the text, we derived the cumulative frequency diagram for flares on stars of the three classes. After dereddening, the flare-frequency for flares with energies $\geq 2\,10^{32}$ erg of cTTSs is a factor of two smaller than for wTTSs. No flares on cTTSs were detected at lower energies, because of the detection threshold for cTTSs is much higher than for wTTSs. Note the large difference between flare-frequency of T Tauri stars and the ZAMSSs.

Table 2. Objects in which flares have been detected

wTTSs	Hubble 4, LkCa 1,LkCa 3, LkCa 4, Lk Ca 5, V410 Tau, V819 Tau
cTTSs	BP Tau, CW Tau, CY Tau, FN Tau, DD Tau
ZAMSSs	AP 15, V 486 Per, AP 60, AP 75

Table 3. Objects on which no flares have been detected

WTTSs	Briceño 2, Briceño 3
cTTSs	DE Tau, FM Tau, FQ Tau, RY Tau
ZAMSSs	AP 17, AP 20, AP 25, AP 28, AP 41, AP 56, AP 63, AP 86, AP 100, AP 108, AP 117, AP 118, AP 112, AP 149, AP 189, HE 520, HE 577, HE 699, HE 917

Most of the flares are quite weak, so that the expected change of the continuum is much smaller than the accuracy of our photometry. We thus estimate the energy released in the lines from the change of the equivalent width during the event using the *average* intensity of the continuum (in that night), and assuming that the intensity of the continuum remained constant during the event.

3.2.2. The frequency of flares detected

Using these criteria, we have detected 29 flares in wTTSs, and 9 flares in cTTSs. Quite remarkably, we have detected flares in 80% of the wTTSs, and 56% of the cTTSs, which means that the true percentage has to be even larger than this (Table 2, and Table 3). At first glance, one would conclude that the flare-activity of cTTSs is less frequent than for wTTSs. However, a more thorough discussion is needed.

After dereddening the spectra, we derived the cumulative frequency diagram for flares in the three classes of objects. Fig. 12 clearly shows that the detection limit for flares on wTTSs is much lower than the detection limit for flares on cTTSs. The reason for this is that the extinction is generally higher for cTTSs than for wTTSs. Moreover, cTTSs are slightly fainter, and often have Hβ in emission. If we take all these factors into account, we find that the detection limit for flares is on average higher for cTTSs than for wTTSs by a factor of 2.7. A similar factor can be read off the diagram, if the two smallest flares of the wTTSs are discarded. This means that we have not detected flare smaller than $2\,10^{32}$ erg in cTTSs because of the detection limit, not because of the absence of such events. By counting all events with energies above $2\,10^{32}$ erg, we find that the difference between the flare rates of wTTSs, and cTTSs is about a factor of two.

However, this result might be influenced by two factors. First of all, it has to be kept in mind that cTTSs have a large spread in brightness, extinction and emission lines strength. Thus, the detection limit is not a sharp boundary, and it is likely that we are missing events also above the $2\,10^{32}$ erg limit. Secondly, as mentioned before, it is difficult to distinguish flares from other types of variations in cTTSs. It is thus possible that to many "flares" were found in cTTSs. Since the two effects work in opposite directions, we may hope that they partly cancel each other, and that the factor of two for the difference in the intrinsic flare-frequencies is roughly correct.

In contrast to the T Tauri stars, only 16% of the sample of ZAMSSs observed showed any signs of flare activity. We detected only 4 flares in these stars, compared to 38 in the T Tauri stars. This result is quite striking, since the total monitoring time of ZAMSSs is comparable to the monitoring time of the T Tauri stars (695 hours compared to 855 hours). In this case, the differences in the number of flares detected can not be explained by differences in the detection limit. If we take into account the factors mentioned above, and additionally the difference in the distance of the two regions, we find that the detection limit is only marginally higher by a factor of 1.2 for the ZAMSSs than for the wTTSs. A χ^2-test shows that the probability that the flare frequency for wTTSs, and ZAMSSs are different is larger than 0.995. We thus conclude that the *average* flare-frequency for wTTSs, is roughly a factor of ten larger than that for ZAMSSs. Numerically, we find a flare-frequency of $\sim 0.006\,\mathrm{h}^{-1}$ for ZAMSSs, and of $\sim 0.06\,\mathrm{h}^{-1}$ for wTTSs, with our detection limits.

4. Discussion

4.1. Comparison of the flare-frequency in the optical and in the X-ray region

In order to compare the flare-frequency in the optical and in the X-rays region, simultaneous observations of flares in both wavelength regions are needed. Although such data is not available for T Tauri stars, it does exist for other types of stars. For flare stars, Butler et al. (1988) shows that the total energy released in Hγ is related to the energy released in the soft X-rays band. Using this relation and the observed fluxes of a solar flare in

Hβ and Hγ (Johns-Krull et al. 1997a), we find that the flares on T Tauri stars in Fig. 12 would have energies between 10^{33} erg and $5\,10^{34}$ erg in the 0.25–4.0 keV band. If this is correct, the largest flares in our sample would correspond to the very smallest flares observed by ROSAT in the 0.1–2.4 keV (Preibisch & Neuhäuser 1994). It is thus not surprising that the frequency for flares observed by ROSAT is only $0.001\ \mathrm{h}^{-1}$, (Neuhäuser & Preibisch 1994).

4.2. *Is there a contradiction to previous results?*

At first sight, our conclusion seem to contradict the conclusion drawn by Gahm (1990), and Gahm et al. (1995) as they argue that the frequency of powerful flares is much lower on the cTTSs then on the wTTSs, further substantiated by an extensive UBVRI-monitoring of BP Tau (Gullbring et al. 1996). Despite the different conclusion drawn these authors and by us, all data-sets can be explained, as we will discuss in the following. First of all, from our measurements we conclude that there is a difference of a factor of two between the intrinsic flare rate of the cTTSs, and wTTSs. If we take the difficulty in distinguishing flares from erratic variations of the equivalent width into account, this factor may even be somewhat larger than two. Secondly, the larger extinction in cTTSs than in wTTSs implies that less flares are detected in the cTTSs if flares are search for by observing in the U and B-band. For our sample of wTTSs, and cTTSs we thus conclude that the observed difference between the flare-frequency of cTTSs, and wTTSs would be a factor of four, or even somewhat larger than this. The conclusion drawn by Gahm (1990), and Gahm et al. (1995) is thus in general agreement with our measurements: The observed flare rate of cTTSs is much lower than that of wTTSs, no matter if photometry, or spectroscopy is used. However, it is still surprising that Gullbring et al. (1996) did not detect any micro-flare activity in the cTTS BP Tau.

4.3. *Flare activity and stellar evolution*

From the data presented in this work, we conclude that the frequency of flares is smaller for ZAMSSs than for T Tauri stars. This may imply an evolutionary trend, in which the flare-frequency declines with age.

A similar trend is observed in the X-ray data, as both, the typical energies of flares, and the X-ray luminosity in quiescence declines steadily in the evolution of a star (Preibisch & Neuhäuser 1994; Neuhäuser et al. 1995; Güdel et al. 1997).

5. Conclusions

Using the multi-object spectrograph on the Schmidt telescope in Tautenburg, we have detected flares in ZAMSSs, wTTSs, and cTTSs. We thus conclude that there are flares on cTTSs that can be observed in the optical regime. This result is rather relieving as flares have been detected in cTTSs in the X-ray regime. The properties of these flares on stars of all three kinds are rather similar: All flares show a rapid increase, and a slow decay of the Balmer lines, and even the ratios $\Delta\,E\,(H\beta)/\Delta\,E\,(H\gamma)$ are quite similar. We then derive criteria for the detection of such events, and derive the cumulative frequency diagram for flares on stars of the three classes of objects. We point out that the extinction is a problem for the observations of flares in the optical. We find that the difference of the intrinsic flare-frequency between cTTSs, and wTTSs is about a factor of two for the sample of stars observed.

Together with the fact that we observed flares on 80% of the wTTSs, this implies that a large flare activity is typical for both types pre-main sequence stars. Since only large flares could be detected, this also implies that large magnetic fields are common amongst young stars. In contrast to the T Tauri stars, the frequency (at a given energy) for flares on ZAMSSs seems to be an order of magnitude smaller than that for wTTSs.

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