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Letter to the Editor

ROSAT-detection of a giant X-ray flare on LkHα 92

Th. Preibisch[1], **H. Zinnecker**[1], **and J. H. M. M. Schmitt**[2]

[1] Institut für Astronomie und Astrophysik der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany
[2] Max-Planck-Institut für Extraterrestrische Physik, D-85748 Garching, Germany

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Abstract. We report the detection of a giant X-ray flare on the classical T Tauri star LkHα 92 with the ROSAT PSPC. In this flare the PSPC count rate rose by a factor of more than 100 in a time interval of about 2000 sec. Our X-ray observations cover most of the rise phase as well as part of the decay phase of the flare.

We model the X-ray spectra obtained at different flare phases to determine temperature and emission measure of the flaring plasma. Combining the thus derived X-ray luminosity with the observed decay time scale of $\approx$ 7800 sec, we estimate the total energy release of the flare in the ROSAT PSPC band (0.1 – 2.4 keV) to be $\approx 4 \times 10^{36}$ erg, which is more than a factor of 10^4 greater than the energy release in the strongest solar flares and still more than a factor of 100 greater than that in typical flares on T Tauri stars.

Key words: Stars: flare – Stars: pre-main-sequence – Stars: coronae – X-rays: stars

1. Introduction

The first stellar X-ray flares were detected nearly 20 years ago on nearby dMe dwarf stars (Heise et al. 1975). The number of known X-ray flare stars has been steadily increasing ever since, including in particular RS CVn and Algol systems; Schmitt (1993) argues – on the basis of ROSAT all-sky survey observations – that all types of late-type stars can entertain X-ray flares, though with widely differing timescales. As far as T Tauri stars are concerned, X-ray flares were first observed with the *Einstein* Observatory; cf., Feigelson & DeCampli (1981) for the observation of a flare on DG Tau, Montmerle et al. (1983) for the flare on ROX 20 or Walter & Kuhi (1984) for AS205. A recent review on the flare phenomenon in general and on current problems in solar and stellar flare research can be found in Haisch, Strong and Rodonò (1991). While the quality of the observational data on stellar flares is by necessity far inferior to the data available on solar flares, the interest in stellar flares results from the vastly different energetics, and the X-ray flare on LkHα 92 reported in this letter represents one of the most energetic flare events ever observed.

Send offprint requests to: H. Zinnecker

2. Observation and data analysis

LkHα 92 is a classical T Tauri star located at RA (2000) = $3^h 44^m 26^s$, DEC (2000) = $32° 04' 30''$; the star has a spectral type around K, $m_V \approx 16.5$ and shows Hα emission with an equivalent width of 21 Å(Herbig, priv. comm.). It is a member of the young star cluster IC 348 in the Perseus molecular cloud complex; the distance towards IC 348 is adopted as 300 pc (Strom et al. 1974), but larger distance values can also be found in the literature.

In August 1992 we observed IC 348 with the ROSAT PSPC for a total of 23 675 s. In our pointing LkHα 92 is located only $7.3'$ off axis, well inside the central field of view of the ROSAT PSPC (radius $20'$). The data reduction was performed with the Extended Scientific Analysis System (EXSAS) developed at and provided by MPE. In particular, we performed the small (i.e., <5 percent) corrections for vignetting and dead time with the corresponding EXSAS commands.

2.1. Lightcurve

In order to determine the net count rate we extracted photons from a circular region centered on the source and with a radius of $R_S = 32''$; we estimate that this detection cell contains about 99 % of the source photons since we detect the source only at the highest photon energies. The total number of photons found in the source region is 1765. In order to determine the local background we examined various source-free regions in the vicinity of LkHα 92. Since LkHα 92 is rather isolated (the nearest X-ray source is more than $130''$ away), the background around LkHα 92 appears to be homogeneous and thus an extrapolation of the background should be legitimate. At any rate, the subtracted background count rate (i.e., 3×10^{-4} counts/sec per detect cell) is insignificant compared to the quiescent and flaring source count rates.

The net source count rate is shown in Fig. 1 as a function of time; we chose 100 sec bins in order to be able to resolve the flare rise. The fluctuations in the lightcurve are not significant ($< 2\sigma$) and we are rather certain to see the maximum at the end of phase [1]. We selected only counts recorded in the hard band above channel 50 ($E > 0.5$keV) since the source is detected only in those hard channels where the background is also lower. Also note that only the last observation interval prior to the flare is shown (from a total of nine), and that the pre-flare net source count rate of $(8 \pm 1) \times 10^{-3}$ counts/sec is

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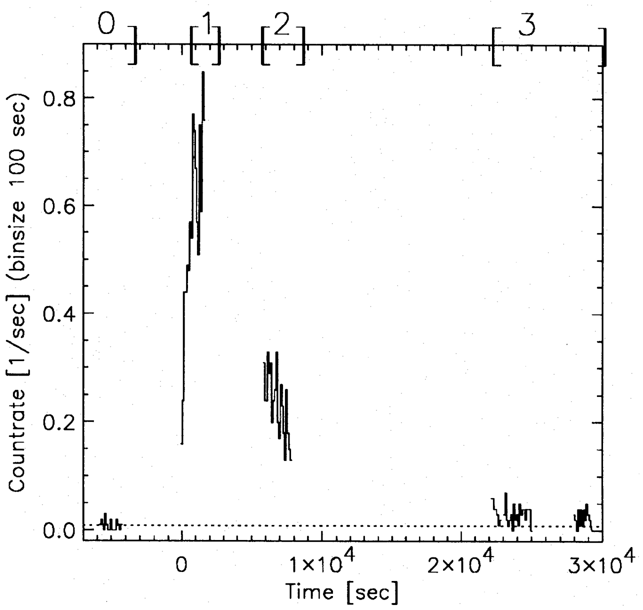

Fig. 1. PSPC Lightcurve of the LkHα 92 flare; t = 0 corresponds to 26 August 1992, 05:01:17 UT

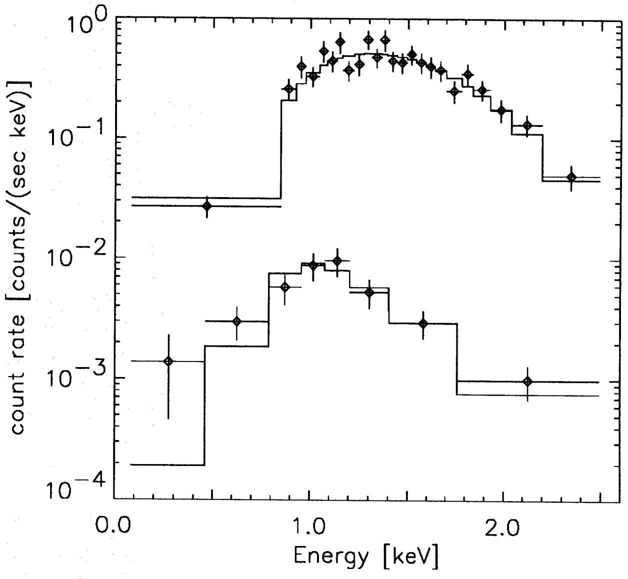

Fig. 2. Count rate spectra (crosses) and best fit spectra (solid line) for the pre-flare stage (lower values) and flare maximum

plotted as dotted line; this quiescent emission level is consistent with the fact that during the ROSAT all-sky survey LkHα 92 was not detected with a 2σ upper limit of 0.04 counts/sec (R. Neuhäuser 1993, private communication). As can be seen from Fig. 1, the maximum net source count rate during our pointed observations in the 100 sec bins is 0.85 counts/sec, more than a factor of 100 above the pre-flare count rate. Further, an extrapolation of the rise phase light curve to the pre-flare level yields a rise time of $\approx$ 2000 sec.

2.2. X-ray spectra

For a more detailed analysis of the flare we investigated the X-ray spectra at the different phases of the flare. We selected four time intervals, as marked on the upper horizontal axis of Fig. 1. The interval 0 contains all pre-flare intervals, interval 1 corresponds to the maximum of the flare and intervals 2 and 3 cover parts of the decay phase.

To obtain the X-ray spectra we used the following procedure: The count rate spectrum of a nearby source-free region is substracted as background from that of the source region. The resulting source count rate spectrum was then rebinned (the counts of several pulse height channels have to be added) to get a specified minimum signal-to-noise (S/N) ratio in each spectral channel. This procedure was carried out seperately for each of the four time intervals. For the interval 0 (i.e., the quiescent level where the count rate was lowest) the minimum S/N ratio had to be set to 3, for the other spectra we chose a minimal signal to noise ratio of 5. In order to give an example of the quality of the background substracted count rate spectra, we plot the spectra obtained at flare peak and in quiescence in Fig. 2.

We fitted our X-ray spectra with the simple model of isothermal optically thin plasma emission (see Raymond & Smith 1977) and interstellar absorption (see Balucinska-Church & McCammon 1992). This model has three free parameters: The temperature T and the emission meassure EM of the plasma, and the column density $N_{\rm H}$ of the absorbing interstellar matter. Using the χ^2 statistics we adjusted the parameters of the model to find the best agreement between the calculated model count rate spectrum and the observed spectrum.

We are of course aware of the fact that such a simple physical model (isothermal plasma) is certainly not able to describe the detailed physics of the flaring X-ray emission. However, the small number of counts in our spectra as well as the modest energy resolution of the PSPC detector do not warrant more complicated models. Since the fits with $N_{\rm H}$ as a free parameter yielded slightly different values for $N_{\rm H}$, we decided to fix $N_{\rm H}$ to a common value for all four spectra. We chose a value of 10^{22}cm^{-2}, a column density consistent with the visual extinction of $A_v \gtrsim 7.5$ found by Bachiller & Cernicharo (1986) for that region. The values for the emission meassure and the plasma temperature obtained in our fits are given in Tab. 1

Table 1. Spectral fit results (for $N_{\rm H} = 10^{22}$ cm^{-2} fixed)

	EM [10^{54} cm^{-3}]	T [10^6 K]	$L_{\rm x}$ [10^{31} erg/s]	χ^2/ν
0	0.3 ± 0.1	11 ± 3	1.0 ± 0.3	0.90
1	48 ± 5	43 ± 16	50 ± 15	0.92
2	19 ± 2	24 ± 6	23 ± 5	0.69
3	1.8 ± 0.4	15 ± 3	3.0 ± 0.7	0.36

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Table 2. Properties of stellar flares at maximum ([1]: Data from Montmerle et al. 1983; [2]: Data from Schmitt 1993; [3]: Data from van den Oord & Mewe 1989; [4]: Data from Tsuru et al. 1983;)

	EM [10^{50}cm^{-3}]	T [10^6 K]	$L_{\mathrm{x,max}}$ [10^{30} erg/sec]	E_x [10^{30} erg]	n_e [10^{10} cm^{-3}]	V [10^{30} cm^3]	l [10^{10} cm]
Sun, compact flare[1]	0.01	≈ 10	10^{-4}	0.1	10 - 100	4×10^{-6}	≈ 0.01
Sun, class 3 flare[1]	$\gtrsim 1$	≈ 10	$\gtrsim 10^{-3}$	$\gtrsim 10$	1 - 10	$\gtrsim 4$	$\gtrsim 1$
EV Lac[2] (dMe)	150	30	0.2	9000	3	16	1.6
Algol[3]	9800	58	16	11 000	24	14	1.5
UX Ari[4]	8×10^4	80	200	$> 10^7$	≈ 1	8×10^4	27
ρ Ophiuchi T Tauri stars [1]	5000	20	≈ 5	$\lesssim 10^4$	10 - 20	30	2
ROX 20 [1]	$\approx 10^5$	≈ 15	≈ 100	$\approx 10^6$	$3-6$	4000	10
LkHα 92	5×10^5	50	500	4×10^6	15	2000	8

together with the merit function χ^2/ν. Inspection of Tab. 1 shows that first of all our spectral fits are acceptable from a statistical point of view. Next, the increase in count rate is due to an increase in emission measure, but there is also evidence for a temperature increase during the flare (as compared to the quiescent emission) with subsequent cooling during the decay phase. Therefore our data on LkHα 92 are fully consistent with the properties of X-ray flares observed on active late-type stars.

From our spectral fits we calculated the X-ray luminosity L_{x}, also given in Tab. 1, by integrating the model spectrum over the ROSAT PSPC energy range from 0.1 to 2.4 keV. The de-reddened values of L_X obviously do depend on the intrinsic X-ray spectrum, which in turn depends on the N_H value chosen. We would like to point out, however, that for the high temperatures determined for the flare the de-reddening correction does **not** sensitively depend on the exact temperature. Because of the large interstellar absorbing column density we can of course not tell whether additional cooler material (with temperatures of, say, a few MK) is also present, and therefore we consider our derived emission measures and X-ray luminosities actually as conservative. As is clear from table 1, the X-ray luminosity at the flare maximum is about a factor of 50 above the pre-flare X-ray luminosity.

3. Results

In order to find the decay time τ of the flare we assumed the X-ray luminosity L_X to have a time dependence of the form

$$L_{\mathrm{X}}(t) = L_{\mathrm{X,0}} + L_{\mathrm{X,f}}(t) \tag{1}$$

where $L_{\mathrm{X,0}}$ is the (quiescent) X-ray luminosity in the pre-flare stage (corresponding to spectrum 0). It turns out that the flare luminosity can be very well described by an exponential $L_{X,f}(t) \propto e^{-t/\tau_d}$ with a decay time scale $\tau_d = 7800$ sec. With this value we can estimate the total flare energy radiated in X-rays as $E_X \approx 4 \times 10^{36}$ erg.

The decay time can also be used to estimate the plasma density if one assumes that no (substantial) energy input occurs after the peak of the flare. This last assumption is essentially *ad hoc*; for example, Schmitt (1993) analysed a ROSAT all-sky survey observation of a long-duration flare on the nearby dMe star EV Lac both in terms of a quasistatic loop cooling model as well as in terms of a continuous reconnection model and found that the observed light curve could be satisfactorily reproduced by both models despite their very different assumptions about the relevant flare physics. If one then does assume no continuous heating, the two main cooling mechanisms are radiative cooling and conductive cooling (Haisch et al. 1991). Studies of the radiative and conductive cooling time scales in the context of solar flares (cf., Moore et al. 1980) and stellar flares (van den Oord & Mewe 1989) typically show radiative and conductive cooling time scales to be of the same order. For our purposes we therefore assume only radiative cooling, where the cooling time is given by

$$\tau_{\mathrm{rad}} = \frac{3kT}{n_e P(T)} \tag{2}$$

Since the radiative cooling function is $P(T) \approx 10^{-24.73} \times T^{0.25}$ erg cm^3/s for $T > 2 \times 10^7$ K with T in K (van den Oord & Mewe 1989), we obtain a plasma density $n_e \approx 1.5 \times 10^{11}$ cm^{-3}.

We can estimate a minimum value of the magnetic field B by equating the magnetic pressure and the gas pressure (Montmerle 1990) and obtain

$$B \approx \sqrt{16\pi n_e kT} \approx 210\,\mathrm{G} \tag{3}$$

This is of the same order of magnitude as the magnetic fields found in solar flare observations (see Haisch et al. 1991) and observations of weak-line T Tauri stars (Phillips et al. 1991).

We can also calculate a characteristic volume V and length l of the flare plasma from the emission measure and the density by assuming

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$$EM \approx <n_e>^2 V \quad \text{and} \quad V = \frac{4\pi}{3} l^3 \tag{4}$$

and find $V \approx 2.1 \times 10^{33}$ cm^3 and $l \approx 7.9 \times 10^{10}$cm.

To test the consistency of these estimates we follow the arguments of Feigelson & DeCampli (1981): Since the disturbance causing the flare will propagate at the Alfvén speed v_A, the caracteristic length should be given by v_A and the rise time of the flare. We obtain

$$l \approx v_A \times \tau_{\rm rise} \approx 2 \times 10^{11} \text{ cm} \tag{5}$$

which is consistent with the characteristic length determined earlier.

4. Conclusions

In Tab. 2 we compare the properties of the X-ray flare on LkHα 92 to X-ray observations of flares on other T-Tauri stars and late-type stars. Note that the values quoted for densities and length scales in Tab. 2 may in some cases slightly differ from those in the papers where the data on the individual stars is presented since we calculated all values in the same fashion as Montmerle et al. (1983). Further note that the X-ray luminosities in particular for the EXOSAT (Algol) and GINGA (UX Ari) observations refer to a different band pass; since we are mainly interested in orders of magnitude no attempt was made to refer all numbers to the same band pass.

Specifically, we consider the small compact and the largest (class 3) flares on the Sun, flares typical for T Tauri stars and the largest T Tauri star flare found in the literature (ROX 20); further we present some examples of flares on dMe stars, Algol and RS CVn systems. Flares on T Tauri stars show a much larger flare plasma volume and total energy release than flares on the Sun; the same applies of course to the largest flares observed on active stars. However, in our observation these quantities are even nearly an order of magnitude larger than in the very large flare on ROX 20, showing that we have detected a really giant flare; the only flare even more energetic than the one observed on LkHα 92 appears to be the large X-ray flare on UX Ari reported by Tsuru et al. (1989).

The main difference between flares on the Sun and on dMe stars and those on T Tauri star flares appears to be the emission measure and hence energetics of the X-ray emitting material; as can be seen from Tab. 2, EM and E_X of the flare on LkHα 92 exceed the values found in the largest solar flares by many orders of magnitude. If our assumption, i.e., the observed decay time scale given - at least approximately - by the radiative cooling time scale, is correct, the derived flare size scales become inevitably very large. In this context we wish to point out that we consider the length scales presented in Tab. 2 as conservative, since they were derived – following Montmerle et al. (1983) – from $EM = 4\pi/3\ n_e^2\ l^3$. In more realistic magnetic loop geometries emission measure and characteristic length scale are related through $EM = N\alpha^2\ n_e^2\ l^3$, where N denotes the number of loops participating in the flare and α the loop aspect ratio. Using the "canonical" values of $N = 1$ and $\alpha = 0.1$, the derived length scales increase by a factor 7.5. Thus also the sizes of the magnetic structures containing plasma of high density are quite different from the X-ray loops found in solar corona. The typical sizes of such loops are characterised by $l/R_* \lesssim 0.1$, while the same ratio is $\gtrsim 1$ in our flare observation (assuming $R_* \approx 2\,R_\odot$). This is consistent with the results of Phillips et al. (1991), who find giant magnetic loops extending to several stellar radii from radio observations of T Tauri stars; however, the relationship between the (presumably) non-thermal radio emission and the (presumably) thermal X-ray emission is unclear at the moment.

If our assumption on the relationship between observed decay time and radiative cooling time is not correct, the coronal densities must be larger and the characteristic size scales correspondingly smaller. For example, if we assume – *ad hoc* – $l = 1.4 \times 10^{10}$ cm, we would require for the flare on LkHα 92 a density of $n \approx 2 \times 10^{12}$ cm^{-3} with a filling factor of unity. Calculating the magnetic field necessary to confine the plasma from Eq.(3), we find coronal magnetic field values approaching 10^3 G. While such large values are certainly not impossible, one would then expect even larger magnetic fields at the photospheric level which is in conflict to observations by Basri et al. (1992) who find (photosperic) magnetic fields at best comparable in strength to those observed on the Sun.

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References

Bachiller, R., & Cernicharo, J., 1986, A&A 166, 283
Balucinska-Church, M. & McCammon, D., 1992, ApJ 400, 699
Basri, G., Marcy, G.W. & Valenti, J.A., 1992, A&A 390, 622
Feigelson, E.D. & DeCampli, W.M., 1981, ApJ 243, L89
Haisch, B.M., Linsky, J.L., Bornmann, P.L. et al., 1983, ApJ 267, 280
Haisch, B.M., Strong, K.T. & Rodonò, M., 1991, ARA&A 29, 275
Heise, J., Brinkman, A.C., Schrijver, J. et al., 1975, ApJ 202, L73
Montmerle, T., 1990, in: *Physics of Star Formation and Early Stellar Evolution*, eds. N. Kylafis & C.J. Lada, p. 1
Montmerle, T., Koch-Miramond, L., Falgarone, E., & Grindlay, J.E., 1983, ApJ 269, 182
Moore R., et al., 1980, in: *Solar Flares*, ed. P. Sturrock, Boulder: Colorado Associated University Press, p. 341
van den Oord, G.H.J. & Mewe, R., 1989, A&A 213, 245
Phillips, R.B., Lonsdale, C.J. & Feigelson, E.D., 1991, ApJ 382, 261
Raymond, J.C. & Smith, B.W., 1977, ApJS 35, 419
Schmitt, J.H.M.M., 1993, ApJS in press
Tsuru, T. et al., 1989, Pub. Astr. Soc Jap., 41, 679
Strom, S.E., Strom, K.M. & Carrasco, L., 1974, PASP 86, 798
Walter, F.M. & Kuhi, L.V., 1984, ApJ 284, 194

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