X-Ray Variability of T Tauri Stars in the ρ Oph Region

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ABSTRACT

We present recent ROSAT HRI observations of two T Tauri stars, SR 9 and SR 12, in the ρ Oph star formation region, already known to be variable both in X-rays and in the optical. Each star was observed six times at regular rotational phase intervals over its rotation period, known from optical photometry.

Significant X-ray variability, on timescales of days, has been detected for both stars in our new HRI data. The X-ray lightcurve of SR 12 shows indications of rotational modulation, while that of SR 9 does not, showing an irregular behaviour. Under the hypothesis that the observed variability of SR 12 is mainly due to spatially inhomogenous coronal structures, as suggested by its periodic modulation, the X-ray variability amplitude is used to put constraints on the degree of spatial uniformity of the corona, and to set an upper limit to its filling factor.

In addition to 'quiescent' modulated emission, the SR 12 lightcurve presents a transient strong count-rate enhancement in one of the six observations. This does not present any evidence of a decay phase over a time span of 20 ksec, such as one would expect for even a strong flare. There is indication of a slow rising phase, that may rather be interpreted as due to the gradual emergence of a very active region above the stellar limb; the observed X-ray lighcurve allows us to estimate its risetime, and therefore to infer the size of the active region.

1 Introduction

We have observed with the ROSAT HRI the part of the ρ Oph region containing the two PMS stars SR9 and SR12. These were chosen for our study since they are known to be highly variable in X-rays from the *Einstein* observations. The rotational period is known for both stars from optical photometry, and they lie sufficiently close to each other that they could be observed both with one HRI exposure.

2 Observations and Data Analysis

Our ROSAT HRI observations were carried out between Aug.29 and Sept.5 1994. Six observations of the same sky region were made at regular intervals, across a time span of 7.2 days. This was chosen to cover simultaneously nearly all rotational phases of both stars SR9 and SR12, whose periods are 6.4 and 3.4 days, respectively (Bouvier 1990). The total exposure time was 28.03 ksec, approximately equally distributed among the individual snapshots. The nominal pointing position was chosen halfway between SR9 and SR12, which therefore lie $10'.1$ far from the optical axis, on opposite sides. Both stars are clearly detected as X-ray sources in all six images.

We have extracted X-ray source counts from a circle of 25 arcsec radius, and background counts from an annulus immediately outside, with outer radius of 50 arcsec. At the off-axis angle of our sources, the total σ of the detector PSF is 6.1 arcsec (David et al. 1993), and therefore 99.97% of the source photons should fall inside the chosen source regions. The total number of net (background subtracted) X-ray source counts are about 870 for SR12 and 1010 for SR9.

We have performed a variability analysis of the X-ray emission of SR9 and SR12 on all time scales up to the stellar rotation period. Each snapshot at a given rotational phase was not made of one uninterrupted observation, but of many (up to hundreds) smaller ones. Thus, even within one snapshot, a clear distinction must be made between detector live time and actual time. The background-subtracted X-ray lightcurves of SR9 and SR12 are shown in the Figures 1 and 2. The size and locations of the time bins used have been chosen to match the actual observation intervals. In the upper edge of the figures time is marked in units of the rotation period of each star. The most evident feature in these lightcurves is the large increase in the count rate of SR12 in the fifth snapshot, likely a flare event. We have studied this event separately from the more 'quiescent' emission of this star. The average count rates for SR9 and SR12, excluding the SR12 flare, are shown as dotted horizontal lines in Figures 1 and 2, respectively.

A Pearson's χ^2 test (Eadie et al. 1971), with the binning scheme of Figure 1,

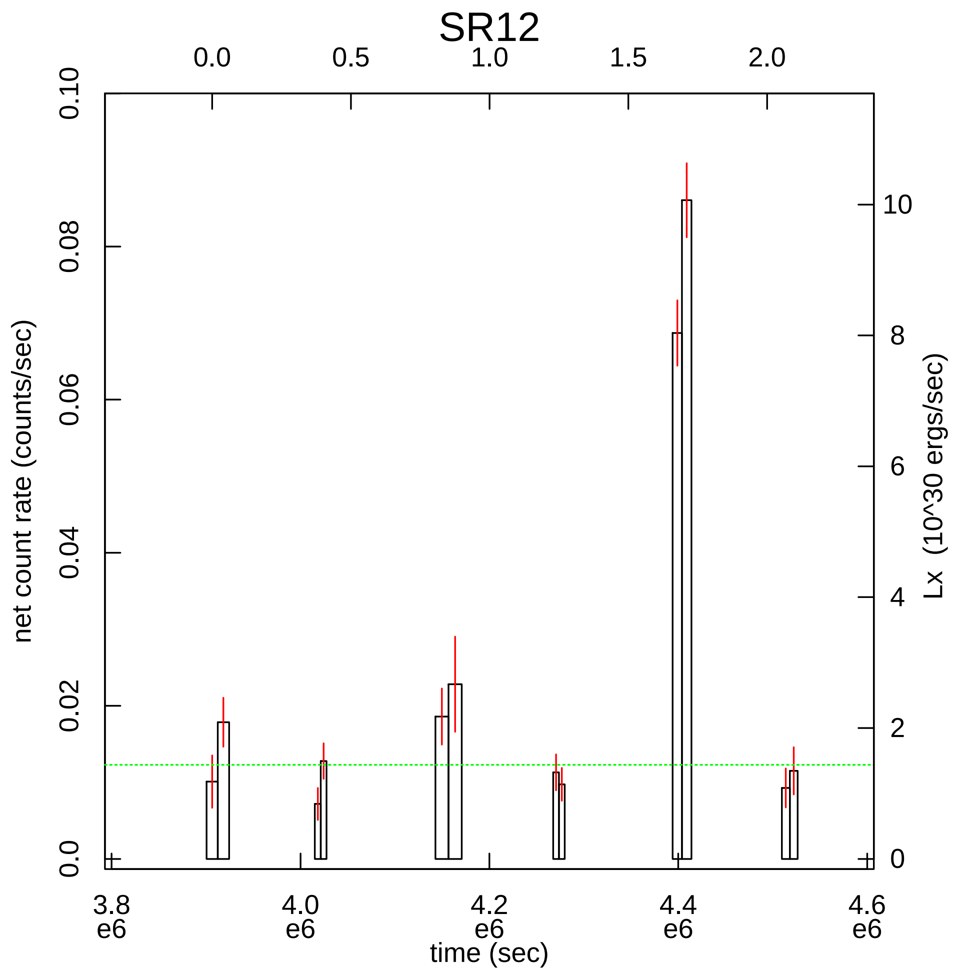

Figure 1: Background-subtracted X-ray lightcurve of the star SR 12. The upper x-axis labels indicate time in units of the stellar rotation period. Assuming that the source spectrum is constant with time, we have labeled the right y-axis with the X-ray luminosity L_x corresponding to the observed count rate. The horizontal dotted line indicates the average (quiescent) emission level, which has been computed excluding the fifth observation interval.

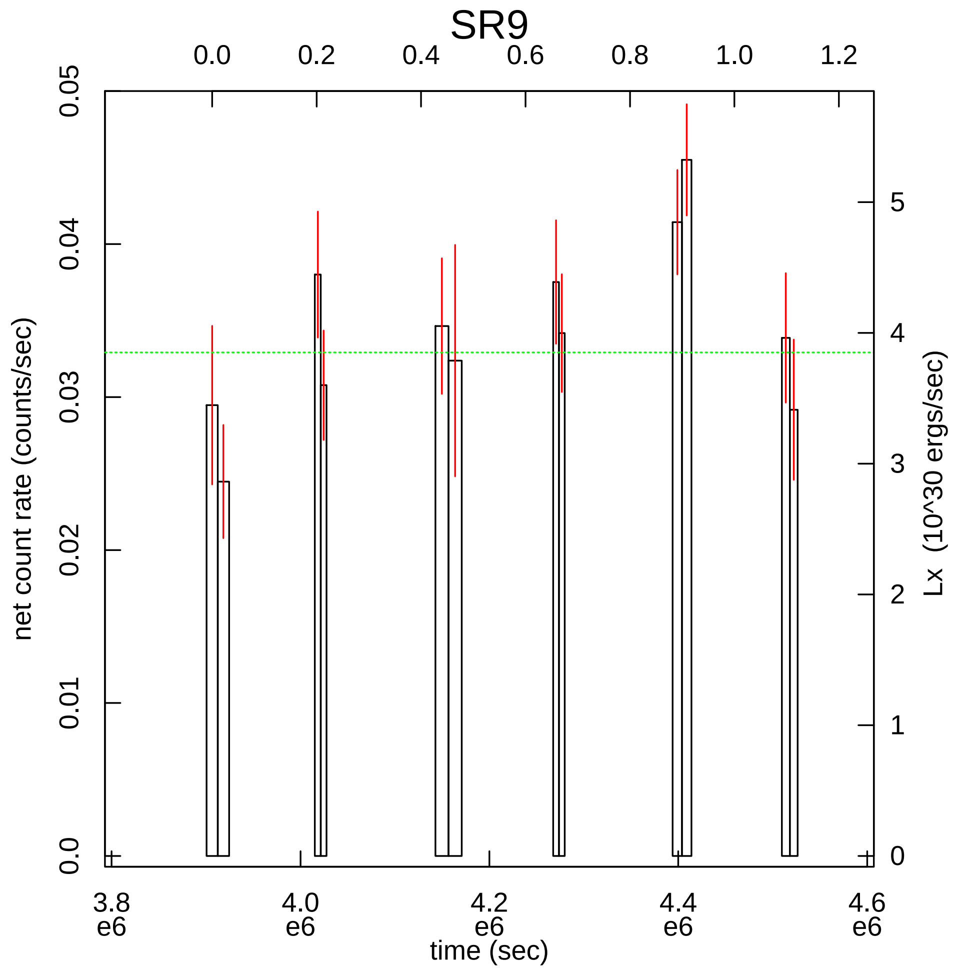

Figure 2: Same as Figure 1, for SR 9. The quiescent emission level (horizontal dotted line) has been here computed including all observation intervals.

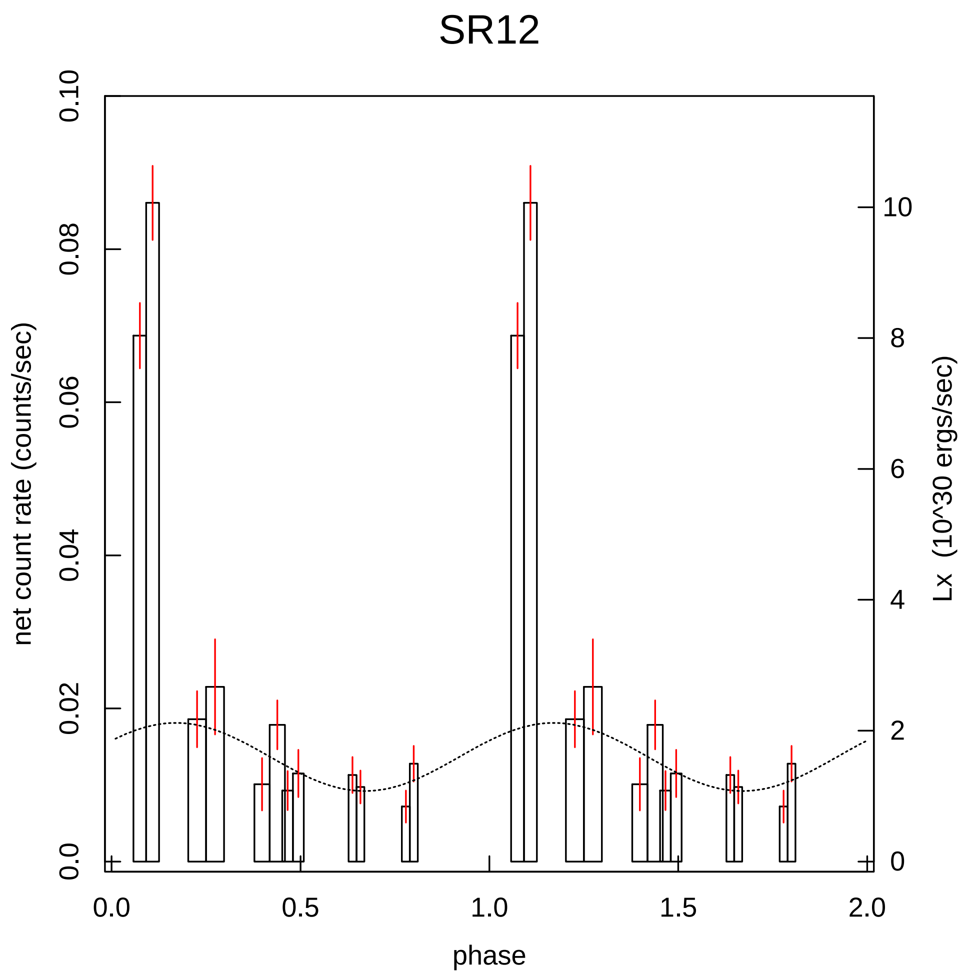

Figure 3: X-ray lightcurve of SR 12 folded with the rotation period. The dotted sinusoid shown yields the best fit to the data (excluding the fifth snapshot). A periodic function fits fairly well the quiescent lightcurve of this star ($\chi^2_{min} = 9.81$ with 7 d.o.f.).

yields a probability of 99.38% that the X-ray source is not constant for SR9, and a probability of 96.87% for SR12, excluding again the flare event. Therefore, even outside obvious flares, both stars are likely variable in X-rays. We have first studied variability on small time scales within each snapshot, applying again a χ^2 test with five bins per snapshot. This test detects variability with probability >99% in the fifth snapshot of SR12 (the flare itself, which will be studied later), and also variability with probability $\geq$95% in the second and fifth snapshots of SR9. These latter indications of variability are not very significant individually, but become more significant if considered together, since for a non variable source such high values of χ^2 probabilities are expected to occur once every 20 trials, rather than in 2 snapshots out of 6, as we observe.

Besides short-term variations, our aim is to investigate if some X-ray variability in these stars may be due to rotational modulation of the emission coming from coronal regions spatially inhomogeneous over the stellar surface, rather than to time variability proper. Knowing the rotation period P_{rot} from photometry, we have attempted to fit the observed X-ray lightcurve with a function $g(t) = C + A\sin(2\pi t/P_{rot} + \phi)$. The parameter values yielding the minimum χ^2 are found

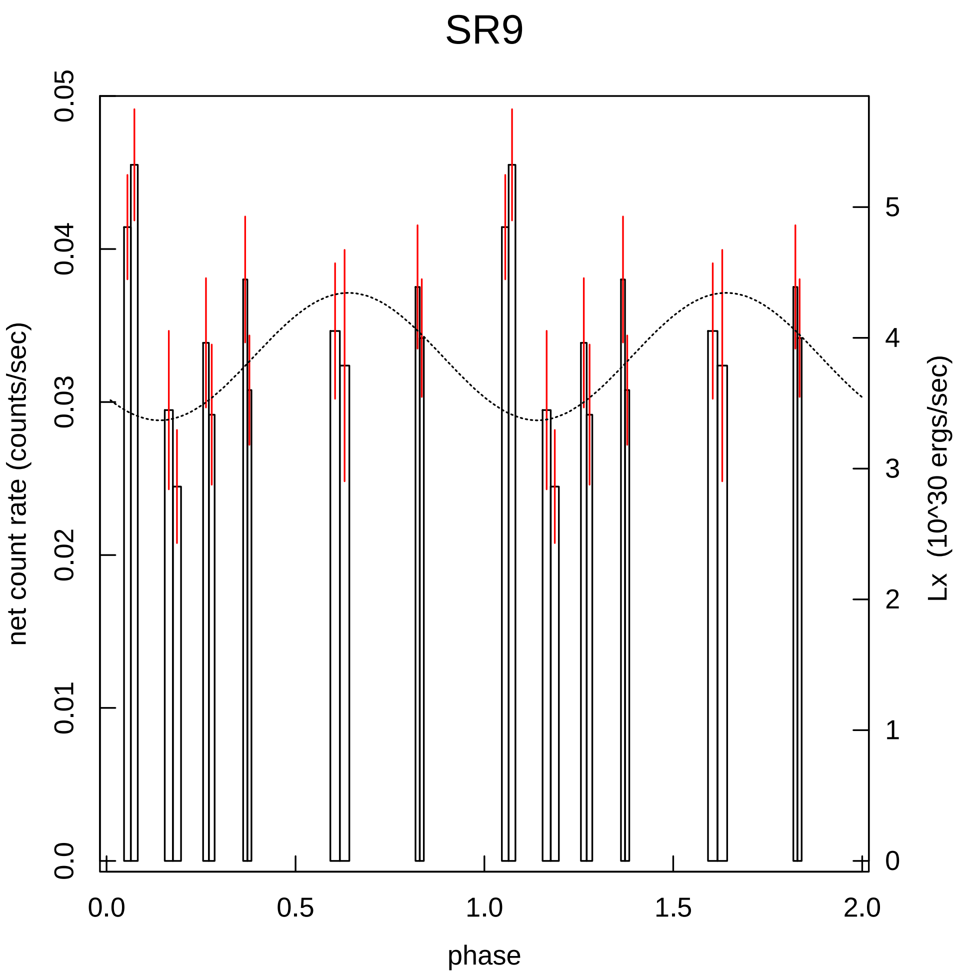

Figure 4: Same as Figure 3, for SR 9. A periodic function (dotted) does not provide a very good fit to the lightcurve of this star.

analytically for A and C, and numerically for the phase ϕ. The lightcurve of SR12, excluding the flare, is fitted quite well with such a model ($\chi^2_{min} = 9.81$ with 7 d.o.f., corresponding to a rejection probability of 80.0%), with $A = 4.4$ cts/ksec and $C = 13.7$ cts/ksec. In Figure 3 we show the SR12 lightcurve folded with the rotation period, and the best-fit model (dotted line). In Figure 5 we show contour levels of χ^2 in the $A - \phi$ plane (after χ^2 minimization with respect to C): shown are contours of $\Delta\chi^2$ ($\equiv \chi^2 - \chi^2_{min}$) $= 2.3$, 4.61, and 9.21, corresponding to probabilities of 68%, 90% and 99%, respectively. The cross indicates the best-fit parameter values. From this Figure it is evident that a fairly well defined minimum of χ^2 exists in the parameter space, which corresponds to a model with a significant periodic modulation of emission, accounting better for the observed lightcurve than a constant source intensity.

The lightcurve fit with such a model is not good for SR9, instead, with a minimum $\chi^2 = 19.73$ with 9 d.o.f., and a rejection probability of 98.03%, only slightly better than a constant source model. The fit improves significantly, however, if one discards the snapshot with the largest count rate (the fifth), which might be a (not obvious) flare event. In this case we get a minimum $\chi^2 = 5.74$ with 7 d.o.f., and a rejection probability of only 43.0%. The best-fit parameters for SR9 are $A = 4.2$

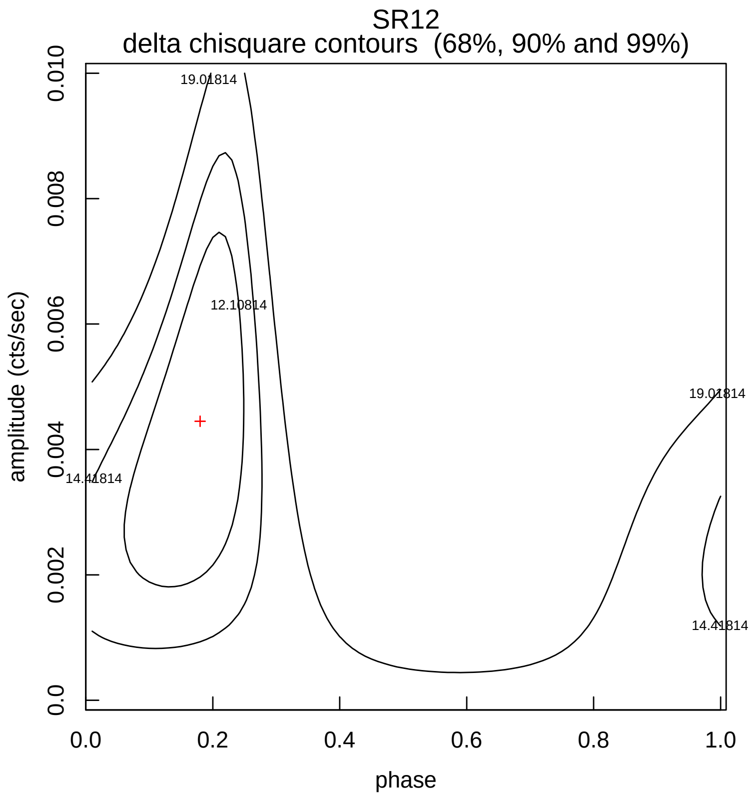

Figure 5: Contours of $\Delta\chi^2$ ($\equiv \chi^2 - \chi^2_{min}$) for SR 12, in the plane $A - \phi$ (modulation amplitude and phase): a fairly well defined χ^2 minimum exists for a modulation with $A \neq 0$.

cts/ksec and $C = 33.0$ cts/ksec. The χ^2 minimum of SR9, however, is not as deep as that of SR12 (Figure 5); moreover, we note that excluding the fifth (flaring) snapshot the probability (given by a Pearson's χ^2 test [Eadie et al. 1971]) that the source is not constant drops to 63.6%, so that there is actually no compelling reason to perform a fit with a periodic model. Also the X-ray lightcurve folded with the rotational period, shown in Figure 4, gives no convincing evidence for a periodic emission component, unlike that of SR12.

2.1 The X-Ray 'Flare' on SR12

The fifth snapshot where SR12 has the largest count rate has a total livetime of 8075 sec, and spans about 20,000 sec. More than 600 source counts have been collected in this time interval. The HRI had an irregular behaviour during this particular observation, resulting in 320 distinct observation intervals (sometimes lasting as little as 1 sec), coming in four main groups separated by 3000-4000 sec. To build a flare lightcurve we have therefore transformed the actual photons arrival times into cumulative live-times, have then made a binning in livetime (taking care of separate observation intervals belonging to different main blocks), and have eventually transformed back the resulting lightcurve in the actual time domain. The lightcurve obtained (background-subtracted) is shown in Figure 7. It is seen that the X-ray emission level stays higher than the quiescent value for

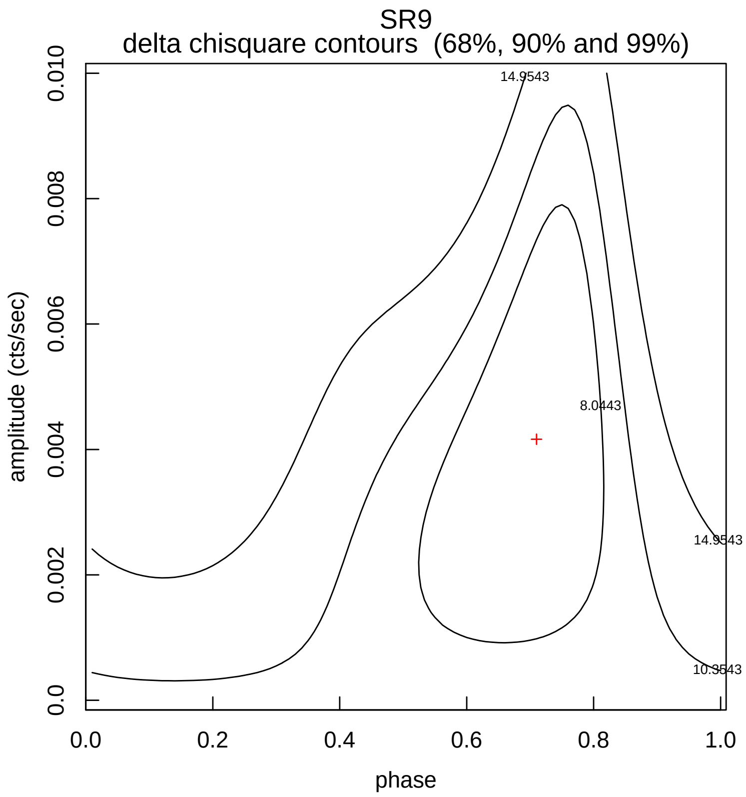

Figure 6: Contours of $\Delta\chi^2$ for SR 9. Even from this plot, there is less convincing evidence for a periodic behavior of X-ray emission in this star (the χ^2 minimum is not very deep).

the whole duration of the snapshot of 20 ksec. There is no apparent decay phase, rather the count rate seems to increase in the first $\sim$ 10 ksec.

We have applied a χ^2 test to the lightcurve shown in Figure 7 to check if it is compatible with a constant source (horizontal line in Figure 7), with the result that a constant count rate is ruled out with a probability of 99.86%. Since no decay is visible, we do not attempt to fit an exponential law to the data; we have instead tried a linear model (count rate steadily increasing with time), although less susceptible of immediate interpretation. A χ^2 fit to the data using such a model gives a minimum χ^2 corresponding to an acceptable low probability of 69.69% of model rejection, and the best-fit line has positive slope (confirming the visual appearance: tilted straight line in Figure 7). Finally, we have attempted to fit the data with a parabolic model (curve in Figure 7), yielding a low probability of model rejection (43.73%), and a *negative* second derivative, which may suggest that a maximum of this flare event occurs within the time span of our observation.

3 Results

3.1 The Distribution of Active Regions on the Stellar Surface

If our interpretation of the observed lightcurve as due to spatial modulation of rather stationary coronal structures is correct, the observed X-ray variability may

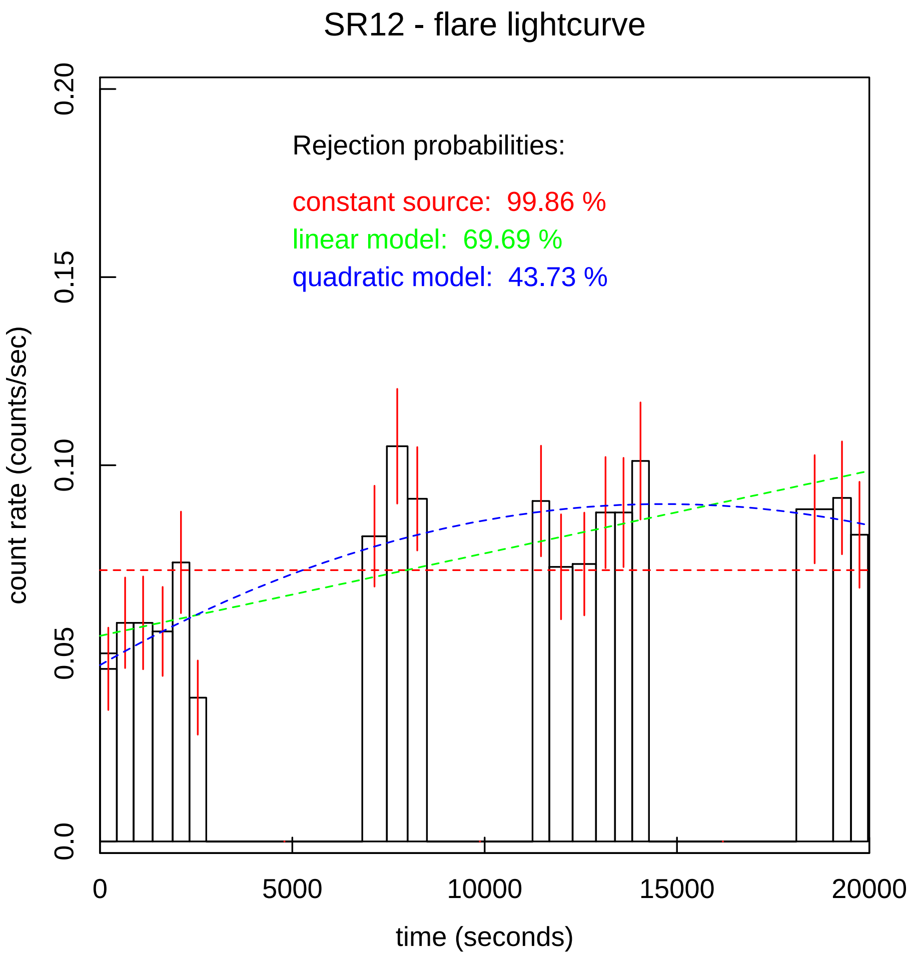

Figure 7: Lightcurve of the fifth observation interval of SR 12. Equal live-time bins are shown (not the same as equal timespan bins), to have similar photon statistics in each bin. We show also schematic models used to fit this lightcurve, and their rejection probabilities.

yield information on the spatial distribution of coronal active regions. For example, the existence of a modulation rules out filling factors f close to unity, and the modulation amplitude puts a rough upper limit to such filling factor. For example, we have derived for SR 12 a relative modulation amplitude $A/C \sim 0.3$, and therefore of a factor of ~ 2 between minimum and maximum emission; if the emission is proportional to the filling factor, f will differ by the same factor between the two stellar emispheres, from which we derive $f < 0.75$ for SR 12.

Otherwise, one may relate the observed coronal inhomogeneity to the randomness of the active region distribution. If every active region emits the same total X-ray luminosity (only as a working hypothesis), say L_x^1, the total X-ray luminosity of the star L_x $(= nL_x^1)$ will fluctuate in time as the number n of active regions in the visible emisphere. We may then write: $L_x \pm \Delta L_x = L_x^1(n \pm \sqrt{n})$ yielding $n = \left(\frac{L_x}{\Delta L_x}\right)^2 = (C/A)^2 \sim 10$. Therefore, under very simplified assumptions, the observed X-ray modulation on SR 12 might be due to a random spatial distribution of about 10 active regions per emisphere.

3.2 Properties of the 'Flare' on SR12

The lightcurve of the strong flaring event reported in Figure 7 shows two main interesting features: first, the count rate rises slowly before attaining its maximum; and second, the lightcurve remains roughly flat over a time span of 13 ksec, without evidence of decay. Flare evolution over such long timescales is observed only very rarely, in the most active stars (e.g. RS CVn's). In dMe flare stars events have been observed with a complex time structure (Pallavicini, Tagliaferri & Stella 1990), analogous to solar two-ribbon flares, but in no case among those studied by Pallavicini, Tagliaferri & Stella (1990) is the risetime so long as in the present case. Also the absence of decay over such a long time is not usually observed in the most active flare stars, and may imply the occurrence of multiple emission peaks. Therefore, the event now observed on SR12 might be a rather exceptional one.

From Figure 7 we can estimate a risetime of ~ 13 ksec, from flare start (~ 6 ksec before the beginning of our observation) to maximum phase (~ 7 ksec after the beginning of our observation). The flare start time evaluated here is close to that given by the parabolic fit of section 2.1. We have also evaluated bounds on the flare decay time T_c by fitting an exponential Ae^{-t/T_c} to the lightcurve since the start of maximum phase, and including also the last observation snapshot, 100 ksec later. The 1σ confidence interval on T_c derived in this way is 45-60 ksec (12.5-16.7 hours), which is again very large with respect to other flare stars.

Since such long rise- and decay times for the intrinsic flare emission seem little plausible, an alternative explanation may be that a more ordinary flare (e.g. with risetime ≤ 3 ksec, followed by exponential decay) is occurring in an active region

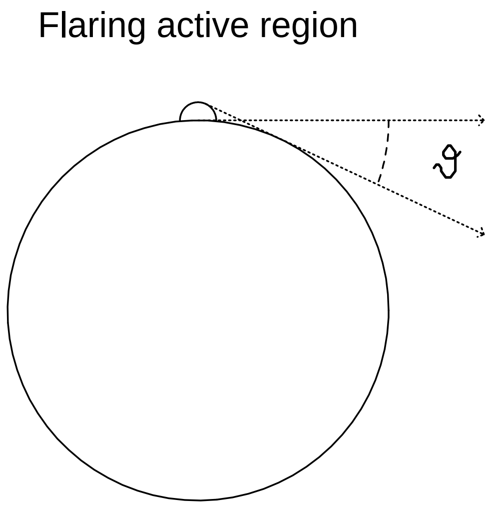

Figure 8: Schematic representation of the active region giving rise to the observed X-ray emission enhancement on SR 12.

just *on the edge* of the stellar disk, which becomes gradually visible as the star rotates. This circumstance, although a priori unlikely, allows us not to invoke an exceptional event to explain our data.

If the observable fraction of the emission from such an active region can be approximated as $f \sim (t - t_0)/\Delta t$ (for $t_0 < t < t_0 + \Delta t$), the observed lightcurve will be proportional to $e^{-t/T_c}\,(t - t_0)/\Delta t$ in this time interval. Including also a normalization A, this is a function with four free parameters (A, T_c, t_0 and Δt). Our lightcurve is however relatively featureless, and we have not attempted a fit with such a complex function. Rather, we rely on the quadratic fit already performed in section 2.1, which suggested the existence of an emission maximum. This may be identified with the maximum of the function $Ae^{-t/T_c}(t-t_0)/\Delta t$, which occurs for $t_{max} = T_c + t_0$. Having estimated t_{max} and t_0 from the parabolic fit, we obtain $T_c \sim 20$ ksec (5.5 hours), a more reasonable value (for a long-duration flare) than those derived before. We note that a quadratic model is a good approximation of the function $e^{-t/T_c}(t-t_0)/\Delta t$ for $t \ll T_c$ (near the start of our observation) since in thic case $e^{-t/T_c} \sim (1 - t/T_c)$.

Since the flare lightcurve remains flat until the end of our snapshot, the complete emergence of the flaring active region above the stellar limb takes a time $\Delta t \geq t_{end} - t_0 \sim 25$ ksec, where t_{end} is the time span of the snapshot (not the livetime). The time Δt is a function of the stellar rotation rate and the size of the flaring region. In analogy with solar active regions, it is reasonable to suppose that the one observed on SR12 has a non-negligible vertical extent. Approximating it as a half-sphere of radius R, we may derive the ratio r between R and the stellar radius $R_\star$, $r = R/R_\star$. With reference to Figure 8, it is seen that such a region passes from invisibility to complete visibility as the star rotates by an angle θ (remember the region is optically thin). Elementary geometry shows that $(1-r) = \cos\theta = \cos(2\pi\Delta t/P_{rot})$. This implies a (minimum) radius for the active region of $R \sim 0.1 R_{\star}$. If our interpretation of the long risetime of this flare in terms of an occultation effect is correct, therefore, we are able to derive spatial properties of the involved coronal structures from the analysis of the X-ray lightcurve.

4 Conclusions

The X-ray monitoring of two T Tauri stars, SR 9 and SR 12, using the ROSAT HRI, has provided some clues on the nature of the X-ray variability of these stars, and on the coronal structures giving rise to X-ray emission.

We have gained more evidence for a strong X-ray variability of these stars: even outside clear flares, their 'quiescent' emission may vary by a factor of two on timescales of 2–4 days, with absolute variation amplitudes of order $\Delta L_x \sim 10^{30}$ ergs/sec.

There is some evidence for a periodic modulation on one star (SR 12), implying an inhomogeneous surface distribution of active regions; the modulation amplitude may then yield constraints on the surface filling factor (or on the number of active regions).

Finally, a strong count rate enhancement has been observed in one observation, unlikely due to a flare. Under the hypothesis that it is due to the emergence of an active region above the stellar limb, we have estimated the size of such region to be of order $0.1 R_{\star}$.

These results, although not conclusive, show nevertheless the great potential of monitoring X-ray observations to derive coronal properties of active stars.

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