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A large X-ray flare on HU Virginis

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Abstract. We present two ROSAT-HRI observations of the RS CVn-type binary HU Virginis (=HD 106225). The first observation covers almost three consecutive rotation cycles of HU Virginis or a total of 26.7 days and an exposure time of 35 ksec. On JD 2,449,544 a long duration flare was detected and observed for 1.5 days. This event was releasing a total energy of $\approx 7.7^{+3.3}_{-1.9} \times 10^{36}$ erg in the 0.1–2.4 keV bandpass. The good coverage of the onset and maximium phase of the flare light curve allowed a detailed comparison with two solar flare models. We derived an estimate for the size of the active region responsible for the flare. The resulting loop size is of the order of one stellar radius. One year later, in 1995, HU Virginis was again observed by ROSAT continuously for 8 days and a total exposure time of 69 ksec. The X-ray flux shows variability on time scales shorter than the rotational period.

Key words: stars: activity – stars: coronae – stars: flare – stars: individual: HU Vir – X-rays: stars

1. Introduction

Since the first observations from space it has been known that stellar X-ray emission is ubiquitous throughout the entire H-R diagram. The EINSTEIN satellite determined X-ray luminosities for all spectral types in the range $10^{26} - 10^{34}$ erg s^{-1}. Only early A-type dwarfs and late M supergiants do not show any detectable X-ray flux (Hünsch et al. 1997). Two approximate correlations for the X-ray luminosity of main sequence and evolved stars were found: for early type stars it is related to the bolometric luminosity and for late type stars to the rotational velocity (Pallavicini et al. 1981). RS CVn-systems were found to be among the brightest sources with X-ray luminosities of $\approx 10^{31}$ erg s^{-1}. The variability of RS CVn-type stellar coronae, especially the most prominent type of variability i.e. the occurence of energetic flares, was observed at several occasions in the past. Charles et al. (1979) first detected a flare on the active RS CVn-type binary DM UMa using a HEAO-1 observation. Further X-ray flares were found by EINSTEIN and EXOSAT for various spectral types, from dMe-stars, RS CVns and Algols to solarlike G-stars. The ROSAT contribution to the exploration of stellar X-ray flares already started during the ROSAT all-sky survey (RASS). On HD 197890, also known as "Speedy Mic", a young K0V Star of the AB Dor type, the strongest flare in terms of count rate was detected during the RASS (Kürster 1995). The peak energy-release rate of this event was $\approx 2.2 \times 10^{36}$ erg s^{-1} in the PSPC bandpass (0.1–2.4 keV) and lasted for 0.7 days, that is about two times longer than the rotational period of 0.3 days. The quiescent emission before and after the flare suggested modulation with a ≈ 0.3 day period, which implies an inhomogeneous corona. The record for the highest measured count rate in a ROSAT PSPC observation in pointing mode, still holds a flare on Algol with 100 cts sec^{-1}, which is equivalent to an output of 2×10^{32} erg s^{-1} (Ottmann & Schmitt 1996). A very energetic flare was observed on the T-Tauri star P1724, with a total energy released in the PSPC bandpass of 5×10^{37} erg, assuming that P1724 belongs to the Orion constellation, which is somewhat uncertain (Preibisch et al. 1995). The longest known X-ray flare was presented by Kürster & Schmitt (1996), who detected a flare on the RS CVn binary CF Tuc with a total duration of 9 days, three times longer than the rotational period. This event released 1.4×10^{37} erg in the PSPC bandpass. Graffagninio et al. (1995) even proposed the idea of an "interbinary" flare, since the size of the flare observed on HR 5110 had about the same dimension as the binary separation.

2. Observations

2.1. The HU Virginis system

HU Vir (K0 III-IV, $P_{\rm rot} \approx 10.4$ days, $v \sin i = 25$ km s^{-1}, $V = 8.7$ mag) is a rapidly rotating K0 star in a close binary system with an unseen (presumably late type) secondary component. It shows all classical signs of an "active" RS CVn star: light and color variability (Fekel et al. 1986), strong Ca II H and K emission (Strassmeier et al. 1990), Hα and ultraviolet emission (Fekel et al. 1986), coronal X-ray emission ($L_X = 2.5 \times 10^{31}$ erg s^{-1}

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from RASS; Dempsey et al. 1993) and radio emission (Drake et al. 1989) as well as spectral line variations (Strassmeier 1994).

Our goal for the X-ray observations of HU Virginis was to detect the rotational modulation due to a proposed large coronal loop. An optical study by Strassmeier (1994) produced a pseudo 3D-Doppler map of the lower atmosphere of HU Virginis from rotational mapping. The photospheric and chromospheric maps each revealed two distinctive features 180° apart in longitude. Observations of the periodically varying Hα profiles led Strassmeier to the conclusion that there is significant mass outflow in the middle chromosphere when the larger of the two active regions is visible and inflow when the smaller one is visible. He tentatively proposed that the two active regions are connected by a large coronal loop and that the mass flow structure is confined by a strong magnetic field and possibly is similar to a siphon-type flow. Because it is very likely that the X-ray flux is confined to localized regions in the corona (e.g. oversized flux tubes) the signal should be modulated when these active regions rotate in and out of sight. As mentioned before the X-ray luminosity of late F- to M stars is correlated with rotational velocity as $L_{\mathrm{X}} \sim (v \sin i)^2$ (Pallavicini et al. 1981), but shows a relatively large scatter: part of it is presumably due to rotational modulation. According to the $(v \sin i)^2$ relation we expected an X-ray luminosity of 8 $\times 10^{29}$ erg s^{-1} for HU Virginis. However, the ROSAT all-sky survey already found HU Virginis to be much brighter: 2.5 $\times$ 10^{31} erg s^{-1} according to Dempsey et al. (1993).

2.2. The X-ray flare in 1994

In 1994 HU Virginis was observed from June 15, 20:00 UT, to July 12, 15:00 UT, with a total exposure time of 32.09 ksec, using the ROSAT satellite (Trümper 1983) and the HRI detector (David et al. 1993). All observations were performed in pointing mode. The point spread function of the HRI is such that 99% of the source photons are located within a circular area of 150". The data was binned into 200 sec intervals and the background subtracted. Data reduction was performed by using the EXSAS/MIDAS software (Zimmermann et al. 1994). Due to technical problems of the satellite the initial duration of the observation was cut to one third. The resulting poor phase coverage of the data did not allow the detection of any rotational modulation of the quiescent coronal emission. The count rate varied from 0.1 to 0.4 cts sec^{-1} which is equivalent to an energy release rate of $\approx$ 0.4–1.4 $\times 10^{31}$ erg s^{-1}.

However, on JD 2,449,544 a large X-ray flare was detected and observed for 1.5 days. Fig. 1 shows the light curve of the X-ray emission at that period of time. Flare onset occured at JD 2,449,544.63 corresponding to rotational phase 0.57 using the ephemeris of Strassmeier (1994). The energy output was rising from 0.16 cts sec^{-1} ($\approx$ 5.7 $\times 10^{30}$ erg s^{-1}) at flare onset to 3.85 cts sec^{-1} ($\approx$ 1.4 $\times 10^{32}$ erg s^{-1}) at flare peak. At the end of the observation the emission was still enhanced compared to the quiescent level before the flare, suggesting that the flare was still in progress at that time.

Fig. 2 compares an X-ray image of the quiescent emission of the star to a "snapshot" during the X-ray flare. By using the best-fit two-ribbon model light curve (see Sec. 3.3 and Fig. 5) we obtained a value for the total energy released by the flare according to the count rate to flux conversion given by Schmitt (1997) and the ratio of PSPC and HRI count rate of 3.2 (Kürster et al., 1997). For a given distance for HU Virginis of 125$^{+23}_{-18}$ pc (taken from the Hipparcos Catalogue, ESA 1997) the total energy output in the 0.1–2.4 keV bandpass was equivalent to $\approx 7.7^{+3.3}_{-1.9} \times 10^{36}$ erg.

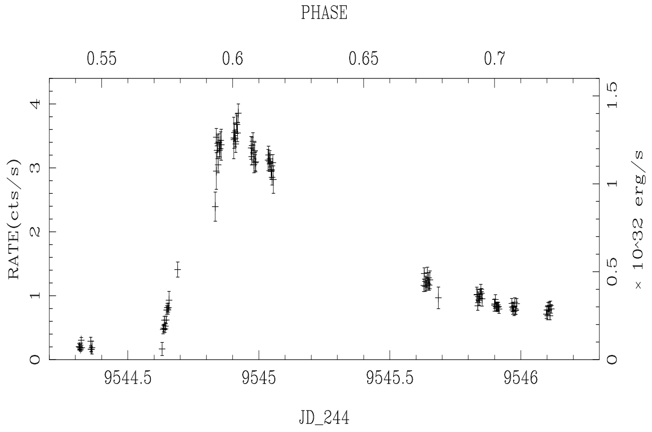

Fig. 1. Background subtracted X-ray lightcurve of the long duration flare on HU Virginis (ROSAT-HRI observation in pointing mode). The X-ray luminosity rises from 5.7 $\times 10^{30}$ erg s^{-1} at the onset to 1.4 $\times 10^{32}$ erg s^{-1} at flare maximum. During 1.5 days the flare released a total energy of $\approx 7.7^{+3.3}_{-1.9} \times 10^{36}$ erg in the 0.1–2.4 keV bandpass.

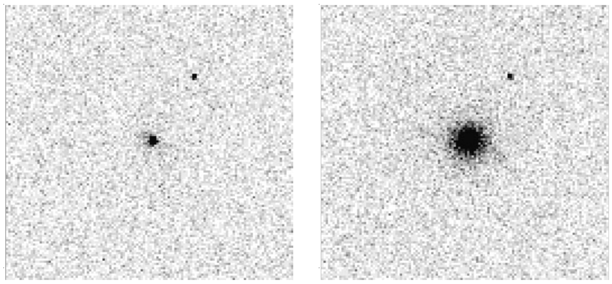

Fig. 2. a (left) ROSAT HRI image of HU Virginis during its quiescent stage, and **b** (right) during the flare. The increase in X-ray brightness is obvious when compared to the constant second source in the field of view.

2.3. Second observations in 1995

Again, from June 18, 20:59 UT, to June 26, 13:00 UT 1995, HU Virginis was re-observed by the ROSAT satellite. The observation was performed in pointing mode using the HRI detector and a total exposure time of 69 ksecs. This time we obtained a far more continuous X-ray light curve that covers almost one complete rotational/orbital cycle. Fig. 3 shows the full background-subtracted light curve of HU Virginis for that time. We distinguish two "levels" of variability: first, significant variations

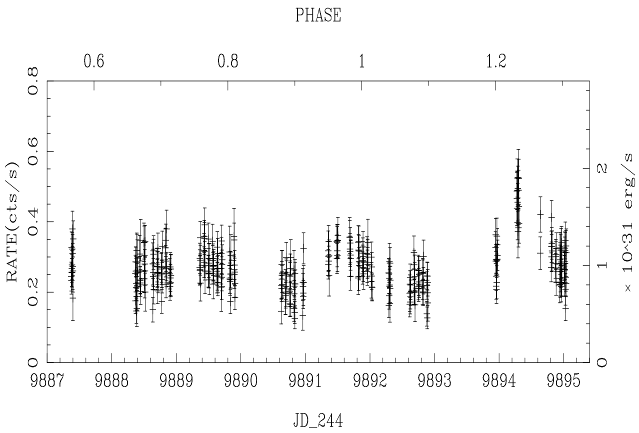

Fig. 3. Coronal X-ray emission of HU Vir during the 8-day observational period in 1995 showing short-term variability. The X-ray luminosity varies between 0.5 and 2 $\times 10^{31}$ erg s^{-1}.

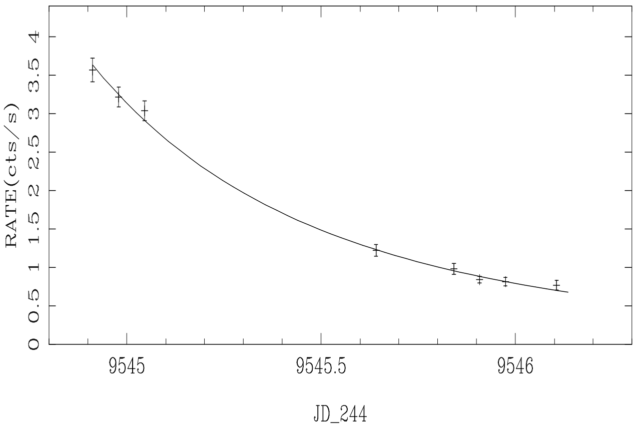

Fig. 4. Decay phase of the flare light curve and the best-fit model of a quasi-static cooling loop with τ=67600 sec.

on a timescale of $\approx$ 2 days and second, a small flare at the end of the observation. Apparently the "quiescent" emission of the corona of HU Virginis still varied between 0.5–1.4 $\times 10^{31}$ erg s^{-1} and reached 2 $\times 10^{31}$ erg s^{-1} during the small flare at around 2,449,894.3. Compared to the 1994 light curve the mean emission level remained the same though.

One question raised by this light curve is whether the apparent "flickering" is just noise or real short-term variability, e.g. microflares. Following the natural grouping of the measurements we subdivided the data into the individual observing slots: JD 2449887.0–88.0, 88.0–89.0, 89.0–90.0, 90.0–91.0, 91.0–92.0, 92.0–92.5, 92.5–93.0, 93.0–94.0, 94.0–94.4, 94.4–95.2. Examination of the data distribution in these "slots" showed that the standard deviation σ of the data from their mean value is of the same size as the typical error. Therefore no evidence of variability on timescales shorter than two days is present.

3. Flare modelling

Both models that we will apply to the X-ray light curve of the 1994 flare of HU Virginis were initially developed to describe solar flares. Since they approach the problem from two different sides it is very interesting to see how consistent the results will be. Earlier applications of these models to ROSAT observations of long duration flares were discussed by Schmitt (1994) and Kürster & Schmitt (1996).

3.1. Rebinning the light curve

Since both flare models just describe the long-term trend in the light curve and cannot account for the fine structure in the onset and at the beginning of the maximum, we rebinned the data into one point per ROSAT-observation "slot" (which typically lasts for 2000 seconds) by taking the mean of all original points weighted with the inverse error. As a conservative approach we adopted the standard deviation of all (original) data points within a slot from the slot mean value as the error of the new points. These rebinned values are shown in Figs. 4 and 5.

3.2. Model 1: a quasi-static cooling flare

The quasi-static cooling loop model of van den Oord & Mewe (1989) assumes that a single coronal loop cools via X-ray emission whitout any further heating (conductive cooling is negligible). This model provides information only for the decay phase of the flare light curve and does not consider the flare onset and thus the heating mechanism. A more detailed description of the model can be found in the paper by van den Oord & Mewe (1989). The radiative energy per unit time released during the flare is given by:

$$E_{\mathrm{rad}} = \frac{E_0}{(1 + t/3\tau)^4} \tag{1}$$

where E_0 is the radiated energy at the peak of the flare, t is the time counted from flare peak, and τ is the radiative cooling time:

$$\tau = \frac{3kT_0}{n_0 \Lambda(T_0)}, \tag{2}$$

T_0 is the temperature at the peak of the flare, n_0 the particle density and $\Lambda(T_0)$ the emissivity or radiative cooling function. From a χ^2-fit to the decay phase, using τ and E_0 as free parameters, we obtain the best value for the radiative cooling time of τ=67600 $\pm$ 3600 sec and E_0=3.63 $\pm$ 0.15 cts sec^{-1}. The errors indicate the 68% ("1σ") confidence region for two parameters using the method described by Lampton et al. (1976).

This best-fit model is plotted along with the observed decay phase of the flare in Fig. 4. Since we have no spectral information with the HRI detector we must estimate the peak temperature T_0 and the emission measure EM_0 by using values from PSPC observations of similar X-ray flares on other RS CVn-type stars. We adopt T_0 = 5.8 $\times 10^7$ K and EM_0 = 7.3 $\times 10^{54}$ cm^{-3} from the CF Tuc flare (Kürster & Schmitt 1996). The value of EM_0 has to be adjusted to the lower sensitivity of the HRI detector (by a factor of 3.2, Kürster et al. 1997), the greater distance of HU Viriginis (125 pc compared to 54 pc for CF Tuc) and the lower countrate. We thus derive $EM_0 = 1.6 \times 10^{55}$ cm^{-3} for the flare on HU Virginis. For the plasma density at the peak of the flare we obtain $n_0 = 2.19 \pm 0.12 \times 10^{10}$ cm^{-3} and for the flare volume we find $V = 3.34 \pm 0.35 \times 10^{34}$ cm^3 using the relation $EM_0 = n_0^2 V$. Having an estimate for the total flare volume we may further estimate the flare extension based upon a single-loop model. We may use $V = \frac{\pi}{4}\alpha^2\ell^3$ where ℓ is the total length of the loop and α is the ratio of the loop diameter $2r$ to the total length ℓ of the loop. From solar analogy, where a typical value of α is 0.1, we derive $\ell \approx 1.62 \pm 0.06 \times 10^{12}$ cm $\approx 23\ R_\odot$ $\approx 4\ R_{\mathrm{HUVir}}$ ($R_{\mathrm{HUVir}} \approx 5.6\ R_\odot$ for the K-star). Approximating the height H of the loop as ℓ/π (which is not exact of course, since the loop is not a half circle), we find $H = 5.2 \pm 0.2 \times 10^{11}$ cm $\approx 7.4\ R_\odot \approx 1.3\ R_{\mathrm{HUVir}}$. Since we do not know if the flare on CF Tuc was hotter or cooler than the one on HU Virginis, we varied T_0 by a factor of 2 and adjusted the corresponding emission measures from Raymond-Smith plasma models (Raymond & Smith 1977) reproducing the observed peak count rate and redetermined the loop size. For a temperature $T_0 = 1.2 \times 10^8$ K and a corresponding emission measure $EM_0 = 2.27 \times 10^{55}$ cm^{-3} we obtain a loop height of 5.8×10^{11} cm $\approx 8.3\ R_\odot \approx 1.5\ R_{\mathrm{HUVir}}$. For a cooler temperature, $T_0 = 2.9 \times 10^7$ K, and the smaller corresponding emission measure, $EM_0 = 1.29 \times 10^{55}$ cm^{-3}, we obtain $H = 4.8 \times 10^{11}$ cm $\approx 6.9\ R_\odot \approx 1.2\ R_{\mathrm{HUVir}}$. In all cases the resulting loop height is comparable to the stellar radius.

3.3. Model 2: a two-ribbon flare

The two-ribbon flare model (Kopp & Poletto 1984) describes a quite different astrophysical scenario. Most importantly, further heating is implicitely accounted for. The model describes the two-ribbon type flares observed on the Sun where reconnection of an open magnetic field structure delivers the energy from which a certain fraction goes into X-rays. The open field structure was created before the flare by a disruptive event and the emission occurs in an arcade of "post-flare loops". Actually, the energy reservoir of the flare is the difference between the non-potential magnetic field *before* and the potential magnetic field *after* the reconnection. The excess magnetic energy gained by the reconnection of open magnetic field lines shows up as thermal energy of the bright X-ray loops. The model is a 2-D field representation of the magnetic field geometry of the flaring region. Again, for more details of the model we refer to the papers of Kopp & Poletto (1984) and Poletto et al. (1989). For our purpose it is sufficient to know that the energy-release rate is given by:

$$\frac{dE}{dt} = \frac{1}{8\pi} 2n(n+1)(2n+1)^2 R_*^3 B_{\mathrm{m}}^2 [I_{12}/P_{\mathrm{n}}^2(\theta)] \times \frac{y_1^{2n}(y_1^{2n}-1)}{[n+(n+1)y_1^{2n+1}]^3} \frac{dy_1}{dt}, \tag{3}$$

Table 1. Results of two-ribbon flare model fits.t_0 is given in sec and n denotes the order of the Legendre polynomial. Degree of freedom is 8 (11 data points minus 3 free parameters). For the n-values within the 68 % confidence region ($\chi^2 = \chi^2_{\mathrm{best}} + 3.5$) the corresponding t_0-range is given.

n	t_0	χ^2_{red}	t_0-range (68 % confidence region)
2	179000	1.729	...
3	171500	0.756	164500 - 178500
4	168600	0.966	163700 - 173500
5	154000	1.052	151000 - 157500
6	152000	1.178	151000 - 153000
7	159000	1.361	...
17	148000	1.812	...
35	152000	2.102	...

where $I_{12} = \int P_{\mathrm{n}}^2(\theta)d(cos\theta)$, and P_{n} is the Legendre polynomial of the order n that describes the morphology of the magnetic field. y_1 is the upward-motion function of the reconnection point in the corona. Once more it is the solar analogy where this motion was determined as a simple exponential function:

$$y_1 = 1 + H_m/R_*[1 - \exp(-t/t_0)] \tag{4}$$

where t_0 is the time it takes the neutral point to reach its maximum height H_m (R_* is the stellar radius). The parameter n describes the angular width of the flaring region (higher n values correspond to smaller regions).

If one could fit the model to the observational data to distinguish between different values of n one would obtain some information on the size of the active region responsible for the flare. Schmitt (1994) already fitted curves of n=2, 6, and 40 to a long duration flare on EV Lac but found that there is no substantial difference between these curves and all of them gave a reasonable fit to the data. Kürster & Schmitt (1996) also compared theoretical two-ribbon light curves with their highly structured light curve of the flare on CF Tuc. Again, no decision in favour of one model could be made, primarily because of the lack of good coverage of the onset phase of the flare. Fortunately, our observation of HU Virginis covered the onset and the maximum of the flare quite well. During the fit process the upward motion time t_0, the order of the Legendre polynomial n, and the overall normalization were used as free parameters. Table 1 compares the best-fit (smallest χ^2_{red}) results for different model parameters. Degree of freedom is 8 (11 data points minus 3 free parameters) hence $\chi^2_{\mathrm{red}} = \chi^2/8$.

Four values for n (3, 4, 5 and 6) and t_0-values from 151000 to 178500 sec are located within the combined 68 % confidence region for 3 parameters ($\chi^2 = \chi^2_{\mathrm{best}} + 3.5$ according to Lampton et al. 1976). These values correspond to latitudinal widths of the flaring region from 60° to 30° and maximum heights of the flaring loops between 0.5 and 1.05 R_{HUVir}. Fig. 5 shows the two-ribbon model light curve with the smallest χ^2-value (n=3 and t_0 = 171500 sec) compared to the observed flare light curve of HU Virginis. The maximum height H_m of the neutral point for such a large flare is 4.2×10^6 km $\approx 5.9\ R_\odot \approx 1.05\ R_{\mathrm{HUVir}}$.

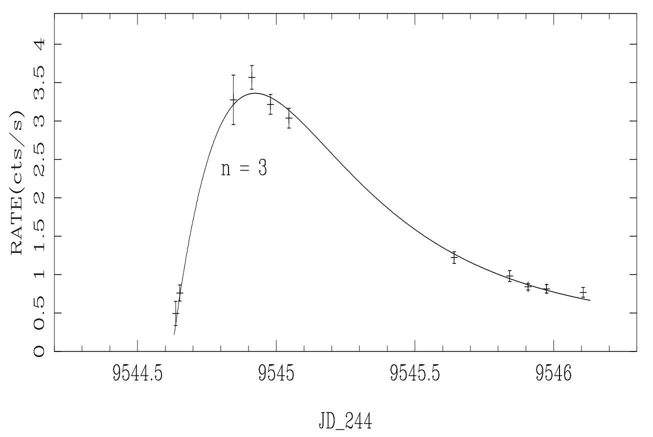

Fig. 5. Best-fit two-ribbon flare model (n=3 and t_0 = 171500 sec) compared to the observed X-ray light curve.

4. Discussion and summary

With a total of $\approx 7.7^{+3.3}_{-1.9} \times 10^{36}$ erg this X-ray flare on HU Virginis released within 1.5 days 55^{+23}_{-14}% of the energy of the exceptional 9 day long flare on CF Tuc (1.4×10^{37} erg, Kürster & Schmitt 1996). Previous observations of X-ray flares on RS CVn-type stars already included events of even greater magnitude: Pye & McHardy (1983) discovered a strong flare on the (presumable) RS CVn-binary 3A1431-409, that released a total of 3×10^{37} erg in the significantly wider (2 – 10 keV) bandpass of the ARIEL-V SSI. Another very energetic flare was seen by Charles et al. (1979), who estimated a total energy release of $\approx 4 \times 10^{37}$ erg in the 0.2 – 2.8 keV for the flare on DM UMa.

In contrast to previous ROSAT observations of long duration flares, our well covered onset and peak of the flare on HU Virginis allowed a more detailed comparison with flare models. In the case of the X-ray flare on EV Lac the onset of the flare was not covered at all, hence no decision in favour of a particular two-ribbon model could be made (Schmitt 1994). The highly structured light curve of the very long flare on CF Tuc, perhaps including multiple flaring events and geometrical effects (CF Tuc is a partially eclipsing system), also did not enable a specific solution for both the quasi-static cooling loop- or the two-ribbon flare model (Kürster & Schmitt 1996). Table 2 summarizes the results for the loop sizes we obtained by using these two models. In the case of the two-ribbon model the given loop size corresponds to the maximum height which the flaring loops reach in the corona. Note that both models, although they describe the flare event completely differently, yield similar and very large loop sizes. Despite that we are able to favour a specific solution within the framework of each flare model, the current data do not allow a firm decision between these two best-fit models.

It is not surprising that we cannot detect any rotational modulation during the flare light curve since the flare duration of 1.5 days is small compared to the rotational period of 10.4 days and furthermore we seem to deal with a spatially extended flare, perhaps even a flare occuring in the polar region of HU Virginis where previous Doppler images showed a major polar spot (Strassmeier 1994).

Table 2. Range of loop heights derived by flare modelling

Flaremodel	Loop-height [R_{HUVir}]
Quasi-static-loop	1.2 – 1.5
Two-ribbon flare	0.5 – 1.05

Our main results can be summarized as follows:

1. We detected a long duration flare on HU Virginis lasting more than 1.5 days and a total energy output of $\approx 7.7^{+3.3}_{-1.9} \times 10^{36}$ erg in the 0.1 – 2.4 keV bandpass.
2. The well covered flare onset and maximum phase allowed detailed comparison with two solar flare models and provided an estimated size of the flaring region. In both cases the resulting size of the flaring region is very extended with the (maximum) height of the coronal loop being comparable to the stellar radius.
3. A continuous 8-day observation revealed variability of the X-ray flux on time scales shorter than the rotational/orbital period. The mean emission ("quiescent") level of the corona of HU Virginis did not change over a year. Within the precision of our data we found no evidence for very short-term variability which could be interpreted as microflaring.

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