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ABSTRACT

Evidence for coronal heating by chromospheric evaporation in flares of active dMe stars is presented through observations of the Neupert effect in high-frequency microwaves and soft X-rays. The Neupert effect, as originally found in solar flares, manifests itself in a close similarity between the soft X-ray light curve and the time integral of the simultaneous microwave light curve. It is interpreted as the signature of the accumulation of hot plasma due to heating by accelerated electrons in the chromosphere.

We used the ROSAT and ASCA soft X-ray observatories and the Very Large Array (VLA) radio telescope (at 6 cm and 3.6 cm wavelengths) to simultaneously monitor the nearby dMe flare star binary Gliese 65 A+B = UV Ceti during 9 hours each on two consecutive days. We find several weakly polarized radio events that start contemporaneously (within a few minutes) with X-ray flares and then peak and decay as the X-ray flares develop gradually. A striking similarity with the temporal evolution of solar gradual events is found. We argue that the Neupert effect is best observed in relatively hard bands of the soft X-ray emission, but that its presence can be inferred

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from the much softer bands commonly used for stellar observations by use of the solar analogy. Together with spectral hardness observations of soft X-rays, the data suggest the operation of chromospheric evaporation on UV Ceti. The observations thus indicate a *causal* relation between the nonthermal and thermal energies of the underlying electron populations.

We find that stellar flares are, relative to solar flares, X-ray weak. The ratio between the total energy radiated into the radio and the soft X-ray bands closely matches the corresponding ratio between the quiescent luminosities of active stars, perhaps implying similar mechanisms and similar efficiencies for the quiescent emission and for larger, single flares. Estimating the total kinetic energy in the electrons from the radio flux, we find that only a part is observed in soft X-rays, a discrepancy well known from solar flares.

Subject headings: stars: chromospheres – stars: coronae – stars: flare – stars: individual (UV Ceti) – Radio continuum: stars – X-rays: stars

1. Introduction

Observations of solar coronal flares have established the transient presence of (a) very hot ($> 10^7$ K) plasma as observed in soft X-ray (~ 0.1 – 10 keV) or EUV (~ 0.01 – 0.1 keV) emission, (b) nonthermal electron populations as observed in hard X-rays (HXR) between ~ 20 keV and ~ 100 keV, and (c) mildly relativistic electrons as evidenced by radio emission at centimetric wavelengths. Under typical coronal conditions, microwave emission is radiated by electrons of several 100 keV to several MeV by the gyrosynchrotron process in closed magnetic fields with strengths of up to a few 100 Gauss. The hard X-ray emission from solar flares reveals a close temporal correlation with microwave emission (e.g., Lu & Petrosian 1990); time delays of the peak emissions in the impulsive phase amount to some 0.2 s on average (Cornell et al. 1984; the microwaves are delayed). The peak fluxes of microwave and simultaneous HXR flares also correlate over orders of magnitude (Cliver et al. 1986; Kosugi, Dennis, & Kai 1988). This suggests that the HXR and the radio emitting electron populations are part of the same nonthermal high-energy tail of the electron energy distribution, most frequently described as a power-law distribution of the form $N(\epsilon) = N_0\epsilon^{-\delta}$, N being the number density of electrons per keV at the energy ϵ (e.g., Dennis 1988). The importance of nonthermal particle energies in the flaring solar corona has been summarized by Hudson & Ryan (1995).

Hard X-ray emission is too weak to be readily detected from *stellar* coronae. Microwaves therefore provide the most direct evidence and the best tracer for the presence of energetic electrons in stellar coronae. In contrast to the Sun, however, coronae of active stars (e.g., dMe stars, RS CVn binaries, FK Comae-type stars) maintain a hot plasma and a “quiescent” nonthermal microwave component during times when no obvious flares are occurring, suggesting that flare-like mechanisms

of particle acceleration and coronal heating operate at all times in their coronae (e.g., Güdel 1994). The quiescent microwave and X-ray luminosities of active stars are approximately linearly correlated (e.g., Katsova 1987; Drake, Simon, & Linsky 1989; Güdel et al. 1993; Güdel & Benz 1993; Fox et al. 1994). This indicates that the production of accelerated electrons is closely related to the mechanism of coronal heating in closed magnetic regions. Further, Benz & Güdel (1994) show that a similar relation holds for the time-averaged microwave and soft X-ray radiation from solar flares, but the solar flares are comparatively X-ray rich. Nevertheless, it suggests that the relevant mechanisms for quiescent coronal emission from stars are similar to the solar flare mechanisms, and that flare heating may make an important contribution to the overall energy budget of active stellar coronae. Similarly, for dMe flare stars, Doyle & Butler (1985) point out that “the quiescent coronal [X-ray] emission is proportional to the time-averaged energy of flares in the U band,” emphasizing the relation between flares and the heating processes of the coronae.

In a standard solar flare model, a considerable portion of the total energy is released in the form of accelerated electrons in the corona. In closed magnetic loops, these electrons travel toward the magnetic footpoints in the higher-density chromosphere where they emit hard X-rays through “thick-target” ion-electron bremsstrahlung (Brown 1971); electrons with energies of several hundred keV and large pitch angles will, at the same time, emit high-frequency gyrosynchrotron emission. Some of the high-pitch angle electrons are trapped in the higher regions of the magnetic loops where they radiate low-frequency gyrosynchrotron emission. The bulk of the precipitating kinetic electron energy is transformed into thermal and mechanical energy in the chromosphere. The rapid deposition of energy causes an explosive chromospheric pressure increase so that heated material “evaporates” into the corona (e.g., Antonucci, Gabriel, & Dennis 1984; Hudson & Ryan 1995 and references therein).

In the solar context, this “chromospheric evaporation” flare scenario is observationally well supported (see review by Dennis 1988). The most compelling evidence for significant heating by nonthermal energy deposition is provided by the “Neupert effect”. Neupert (1968) noticed that the time integrals of the radio emission “closely match the rising portion of the X-ray emission.” The original observations used the Fe XXV line flux at $1.87\text{\AA}$ (~ 6.6 keV, formed at very high temperatures), and microwave observations at 2.7 GHz. Later work preferentially employs hard X-rays (e.g., Dennis 1988 and references therein; Dennis & Zarro 1993 for several examples), and frequently compares the soft X-ray light curve derivative with the contemporaneous HXR time history (Dennis & Zarro 1993, Hudson et al. 1994). Antonucci et al. (1984) find support for the chromospheric evaporation model from the similar total energies in accelerated electrons and in the soft X-ray emitting plasma. However, the estimated total energy in fast electrons may easily exceed the total energy measured in the bulk flare plasma (kinetic, thermal, radiated, etc.; Wu et al. 1986). Recently, Hawley et al. (1995) used the EUV emission together with simultaneous optical data as proxies for the X-ray and radio emissions, respectively, to claim evidence of a Neupert effect in an EUV flare increase observed on the dMe flare star AD Leo.

Since flare heating may be an important factor in the energy budget of the corona of an active

star, one might ask to what extent high-energy electrons produced in the frequent flare events contribute to coronal heating; further, whether the connection between particle acceleration and coronal heating operates similarly in flares on active stars as in solar flares; and third, whether the quiescent nonthermal radio and the quiescent, very hot ($> 10^7$ K) X-ray coronae of active stars are maintained by a multitude of “small-scale” flaring events that connect the observed radio and X-ray emissions via the Neupert effect.

To study chromospheric evaporation in complete flare light curves and explore their energy budget, we arranged a coordinated observing campaign on the prototypical dMe flare star UV Ceti using two X-ray satellites (ROSAT, ASCA) and the Very Large Array (VLA) radio telescope². The selected radio and X-ray wavelength regimes are most relevant for this investigation since i) soft X-rays between 0.1 keV and several keV constitute the primary radiative losses of a typical coronal flare plasma, and ii) the radio-emitting accelerated electrons represent the highest-energy and definitely nonthermal tail of the electron energy distribution. The outline of the present paper is as follows: In Sect. 2, we describe our target and the observations, and we present results in Sect. 3. Section 4 discusses the formalism of the Neupert effect, applied to flares on the Sun and on UV Ceti. We also discuss flare energetics and compare radiated energies. Section 5 contains our conclusions.

2. Targets and observations

2.1. The UV Ceti binary

The two components of the active dMe flare star binary Gliese 65 A+B (= UV Ceti A+B henceforth) are located at a distance of 2.6 pc (Gliese & Jahreiss 1991). The components are separated by approximately two arcsec in an orbit with a period of 26.5 yr (Worley & Behall 1973). The spectral types of A and B are both dM5.5e (Gliese & Jahreiss 1991). UV Ceti’s X-ray emission shows flaring and quiescent episodes (Pallavicini et al. 1990), and both components have been detected as radio sources (e.g., Gary & Linsky 1981; Güdel & Benz 1989; White, Jackson, & Kundu 1989). The binary is easily observable in X-rays and microwaves, with X-ray and radio luminosities of $\log L_X \approx 27.6$ (erg s⁻¹) and $\log L_R \approx 13.1$ (erg s⁻¹Hz⁻¹; Güdel et al. 1993). UV Ceti is an ideal target for our study since its “steady” X-ray emission was recognized to be among the most variable in a sample of dMe stars (Butler et al. 1986; Ambruster et al. 1988), paralleled by the presence of numerous small-scale flares in radio observations (Kundu et al. 1988).

²The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

2.2. Observations

We observed UV Ceti A+B on two days in January 1995 as part of the Guest Observer programs of the *Röntgensatellit* (ROSAT) and of the *Advanced Satellite for Cosmology and Astrophysics* (ASCA). The VLA monitored the star simultaneously as long as it was visible from the VLA site. The observing times are listed in Table 1. Due to Earth blocks, both ASCA and ROSAT record data only for typically 40–50 contiguous minutes per Earth orbit of ~ 96 minutes. The X-ray observations provided only sparse data before the start of the VLA observations (scheduling constraints, possible dropouts due to the radiation environment, etc).

ASCA carries four identical X-ray telescopes (XRTs) that feed two *Solid-State Imaging Spectrometers* (SIS0 and SIS1) and two *Gas Imaging Spectrometers* (GIS2 and GIS3; see Tanaka, Inoue, & Holt 1994). The SIS are sensitive to 0.5–10 keV photons with an effective area (combined with XRT) of up to 200 cm² per SIS at 1.5 keV. The GIS are sensitive to higher energies, comprising the ~ 0.8 –12 keV range with maximum effective area of ~ 170 cm² at about 2 keV. The SIS energy resolution as of January 1995 was approximately 3.5% (FWHM) at 6.7 keV, scaling roughly as energy^{-1/2}. The angular resolution of all instruments is modest (order of 1 arcmin). We observed with only one CCD chip per SIS detector (chip 1 on SIS0, chip 3 on SIS1), and consequently used this chip also for the determination of the background count rates.

The *High Resolution Imager* (HRI) onboard ROSAT is a position-sensitive detector based on microchannel plates (see Pfeiffermann et al. 1986 for a description of the ROSAT mission). The angular resolution amounts to approximately 5 arcsec (insufficient to separate the two UV Ceti components). The detector is sensitive to 0.1–2.4 keV photons with little energy resolution. The maximum effective area is ~ 90 cm² at 1.5 keV.

At the time of our observations, the VLA was in its C→D moving array configuration, with 27 antennas operational. For the C band (4.9 GHz/6 cm wavelength, 100 MHz bandwidth) and X band (8.4 GHz/3.6 cm, 100 MHz bandwidth) used here, the synthesized beam widths were approximately 8 arcsec and 4.5 arcsec FWHM, respectively. Although the binary system was not resolved, positional analysis of the X band data allow us to attribute flares to either one of the components. The selected high-frequency bands favor the detection of incoherent gyrosynchrotron radio flares above strongly polarized coherent bursts that are energetically unimportant here.³

³Solar flare radio emission at low ($\lesssim 2$ GHz) frequencies is predominantly due to coherent emission mechanisms (e.g., beam instability, electron cyclotron maser instability, etc.) as implied by their high ($\sim 100\%$) circular polarization degrees, very rapid variability, and narrow bandwidth. This radiation does not require an energetically important number of electrons and shows little detailed correlation with soft X-ray events (apart from the global association with the flare event). The upper frequency bound for coherent radiation is determined by the fundamental or the second harmonic of the plasma frequency or the cyclotron frequency and is thus determined by the maximum coronal electron densities or magnetic field strengths, respectively. Above this threshold, gyrosynchrotron emission dominates. Its contribution to lower frequency emission is less significant since the emission is typically optically thick below a few GHz, resulting in a flux decrease with decreasing frequency (roughly $S \propto \nu^2$). Most radio flares on dMe stars at the frequently used wavelength of 20 cm (1.4 GHz) are due to a coherent emission mechanism as judged from their

3. Results

3.1. The light curves

Figures 1 and 2 present the data sets with simultaneous radio and X-ray coverage for the two observing sessions. Both figures display, from top to bottom, i) the radio light curve (Stokes I), integrated to 60 s and to 300 s bins (the latter shifted by 3 mJy), with 1σ error bars. The flux unit is $1 \text{ mJy} = 10^{-26} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$. The flux was derived from a position coincident with UV Ceti B, but the two stellar images strongly overlapped and were not resolved. Due to low elevation and problematical weather conditions, the VLA data around the X-ray flare at 22:10 UT on day 1 were not useful and had to be flagged. The gaps near 2 UT were used to calibrate fluxes. The radio light curves contain several statistically significant events that we interpret as flares; the radio flares labeled with *a*, *b* and *A*, *B*, *C*, *D* have simultaneous X-ray data and will be discussed in more detail. ii) The circular polarization degree *p* of the radio flux. To recover the flare polarizations, we combined the two intermediate frequencies (IFs) for each polarization mode and then subtracted a smoothed lower envelope to the RCP and LCP light curves in order to eliminate the quiescent contribution, and lastly computed $p = (\text{RCP} - \text{LCP}) / (\text{RCP} + \text{LCP})$. To suppress the strongly fluctuating polarization of the residual noise, we plot *p* only if the flux above the subtracted background exceeds 0.6 mJy and 0.5 mJy for the C band and the X band, respectively. Accumulations of consecutive bins with weak or moderate polarization degrees and significant fluxes are bracketed by vertical lines (gyrosynchrotron flare candidates). iii) The ASCA GIS (average of two detectors) and ROSAT HRI light curves, binned to 128 s (blank $\pm 1\sigma$ error bars and diamonds with error bars, respectively). The HRI count rates were reduced by a factor of 3.8 on the first day to adjust to the GIS count rates. On the second day, the adjustment factor was 3.1 for the flare increase at 6 UT and the flare decay at 22 UT, while it was set to 4.7 for the other (“quiescent” and spectrally softer) intervals. The adjustment factors were derived from flux-to-count rate conversion factors for the HRI and the ASCA detectors; for the former, appropriate conversion factors were taken from the *ROSAT Mission Description* (1992), and for the latter, they were computed from spectral fits to the data. Constant backgrounds of 0.0204 and 0.024 cts s^{-1} were subtracted from the first and the second day light curve, respectively. iv) The ASCA SIS (average of two detectors) and HRI light curves, binned to 128 s. Here, the HRI count rate was adjusted by dividing the count rates by 1.6 on day 1, by 1.28 at 22 UT and 6 UT on day 2 and by 1.95 for the remaining (“quiescent” and spectrally soft) intervals on day 2. The background count rate light curve as determined from the same chip and normalized to the source detection area has been subtracted from the SIS data (order of 0.01 cts s^{-1}). Corrections for differing sensitivity

observational characteristics. A part of the reported dMe star flares at 6 cm (4.9 GHz) share these characteristics, while at higher frequencies, gyrosynchrotron emission appears to predominate (Bastian 1990). Stronger magnetic fields in M dwarf flare stars imply an upper bound for gyromagnetic coherent radio emission at higher frequencies than on the Sun, probably at several GHz (Bastian 1990). We thus intended to use the VLA’s sensitive X band exclusively, but were forced to change to C band on the first day due to bad weather conditions.

in the background and the source areas on the detector were derived from blank sky background observations. For the intervals 3:00–7:10 UT on day 1 and 6:30–7:10 UT on day 2, we separately plot the “hard” radiation, i.e., the photon count rate for the SIS 2–10 keV spectral range. For other intervals, the hard radiation is rather insignificant, and its time history mimics the total count rate. v) The SIS hardness, defined as the count rate ratio between the softer (0.5–2 keV) and the harder (2–10 keV) spectral regions.

3.2. Candidates for the Neupert Effect

If the chromospheric evaporation model holds for the observed stellar flares and the Neupert effect operates similarly as in solar flares, we expect to find pairs of radio/X-ray flares in which (i) the onset times of radio and X-ray emission closely coincide, (ii) the steepest increase in the X-ray count rate occurs when the radio flare reaches its peak, and (iii) the X-ray flare reaches its X-ray peak only when the radio emission has dropped close to pre-flare values.

We summarize in Table 2 coincidences (or conspicuous absence of coincidence) between selected radio and X-ray events. The impulsive radio flare *a* on day 1 (increase within 1 minute and exponential decay) is followed by a gradual enhancement in X-rays with a peak delay of about 10–15 minutes. The strong radio flare *b* and the simultaneous X-ray flare suffer from incomplete coverage between radio and X-ray observations; the X-ray flare peak was probably not observed. Further, its radio circular polarization degree amounts to $\sim 65\%$ at peak flux, so that its characterization as a gyrosynchrotron flare is unlikely (Dulk & Marsh 1982).

The best Neupert effect candidates on day 2 are flare *A* with the accompanying X-ray flare at 3 UT (Fig. 3), and flare *D* with the X-ray flare at 6:30 UT (see Fig. 4). From a positional analysis we find that flare *D* occurred on the primary star (UV Ceti A), while the other flares and the quiescent emission originated from UV Ceti B. Flare *B* is followed by an accelerated X-ray increase toward the flare peak on top of the gradual flare, and is furthermore accompanied by an increase of the SIS hardness and the 2–10 keV photons. The most notable case with no clearly visible accompanying X-ray increase is flare *C*, but the X-ray light curve is still decreasing from the previous flare.

We consider flares *a*, *A*, *B*, and *D* to be viable candidates for the Neupert effect. On a detailed level, however, we observe that for *A* and *D* the X-ray peaks are considerably delayed to what is expected from the Neupert effect; they occur 0.7–1.1 hrs after the radio peak, long after the radio flares have dropped to the noise level. On the other hand, the flare start times are closely coincident; in the case of flare *D*, the first radio increase is detectable at $\sim 5:12$ UT, while the X-rays begin to increase at 5:16.8 UT, i.e., with a detectable delay of only 4–5 minutes. In the impulsive flare *a*, the radio emission starts abruptly and peaks within a minute, at 1:14.3 UT, while the X-rays start between 1:12–1:16 UT and peak between 1:22–1:30 UT. We will interpret the additional X-ray delays in Sect. 4.

3.3. Electron temperatures and spectral hardness

Spectral modeling was used to infer the cross-correlation between the ASCA and the HRI light curves. The ASCA SIS0 detector data proved to be the most valuable for spectral fitting. We fitted temperatures and emission measures of optically thin Mewe-Kaastra-Liedahl (MEKAL; see Mewe, Kaastra, & Liedahl 1995) coronal models as implemented in XSPEC (Vers. 9.01) software package to the combined “quiescent” spectrum (at 24 UT, 2 UT, and 5 UT) and to the “flare” spectrum (at 3 UT and 7 UT) of day 2. The local background spectrum from the same SIS chip was subtracted. We found acceptable fits using three temperature components with solar elemental abundances ($kT = 0.23, 0.68$, and 2.32 keV during quiescence with $\chi^2 = 7$ for 17 spectral bins, and $kT = 0.35, 0.88$, and 3.2 keV during flares with $\chi^2 = 43$ for 36 spectral bins during the flaring section. The hot plasma dominates during the flares). Our multi-temperature result for single flares are understandable since we integrated our spectrum over the complete flare light curve for sufficient photon statistics.

We derived X-ray luminosities for the standard SIS bandpass (0.5–10 keV), and after extrapolation of the model, for the ROSAT bandpass (0.1–2.4 keV). From confidence range simulations, we find statistical errors for the total emission measure, and consequently for the X-ray luminosity of 12–17%. The unknown actual run of the flare temperature(s) introduces some systematic error for the 0.1–2.4 keV X-ray luminosity, estimated to be less than 10% from simulations. The cross-calibration between SIS and HRI is somewhat problematical. The SIS is not optimized to detect cool ($\lesssim 3$ MK) plasma, while the HRI has decreasing sensitivity to plasmas above ~ 10 MK. Using the SIS model for quiescence and applying the flux-to-count rate conversion factors given in the *Rosat Mission Description* (1992) to each temperature component, we expect an HRI count rate of 0.125 cts s^{-1} , matching the detected (unadjusted) non-flare HRI count rates. We therefore believe that the cross-calibration is sufficiently accurate for our purposes. The average $L_X \approx 27.67$ during the complete observation is compatible with earlier reports (Pallavicini et al. 1990; Güdel et al. 1993). We would like to mention that the distinction between quiescent and flaring intervals is somewhat artificial in our observations; the variable flux-to-count rate conversion factors (Sect. 3.1) indicate that variable heating processes (e.g., flares) predominate.

Most of the observed stellar SIS count rate is radiated between 0.5 and 2 keV (see lower panels in Figs. 1, 2), i.e., $\sim 92\%$ during the flares, and $\sim 97\%$ during quiescence. The SIS and GIS light curves are therefore quite similar to what we expect from the ROSAT bandpass alone. Since the temperature history is not available at high temporal resolution, we will employ the hardness ratios to infer trends in heating and cooling. A continuous decrease of the electron temperature (or a relative decrease of the emission measure of the hot plasma) during the gradual X-ray flare associated with flare *D* is suggested in the lowest panel in Figure 2 and Figure 4 where the radiation steadily softens, starting during the increasing part of the flare. On the other hand, during the two flare starts in Figure 1 at 3:20 UT and 6:40 UT, the radiation hardens significantly. Also note that the GIS flux and the SIS hardness drop to nearly zero after the flare-like enhancement during flare *a* at 1:50 UT, and similarly at 5:10 UT.

4. Discussion

4.1. Formalism for the Neupert effect

In the framework of chromospheric evaporation, we assume that the emitted radio emission or its flux at Earth, $F_R(t)$ is at any time proportional to the deposition rate of kinetic energy by nonthermal electrons into the plasma of the chromosphere. This plasma is thereby heated and “evaporates” into the corona. We define the conversion factor α as the ratio between the *thermal* energy flux being deposited in the chromosphere by nonthermal electrons and the observed radio flux density. Conversion into other forms of energy (mechanical, turbulence, etc.) occurs in parallel. Our simplification consists, first, in the assumption that these other energy transformations do not interact so that α remains constant over the course of the relatively short radio flare; second, we will assume that the dominant losses of the *thermal* energy occur via radiation; we will neglect energy loss into cool, non-X-ray emitting plasma, e.g. by conduction, and cooling by adiabatic expansion. Also, we assume that there is no direct heating in parallel to the chromospheric evaporation. Third, we will use one temperature parameter for the flare plasma at any given time: The temperature T can be considered as describing an isothermal plasma dominating the total losses from the flaring loops; this approximation appears to be relatively good for solar flares at least during their decays (Garcia and Farnik 1992). Our energy equation derived below (eq. 1) analogously applies to more sophisticated loop models where T plays the role of an average temperature (see eq. 1 and 3 of Fisher & Hawley 1990).

The conductive term may be of some importance in particular during the initial phase of solar flares (Cargill, Mariska, & Antiochos 1995). On the other hand, during phases of large density increases and declining temperatures, the plasma energy losses are dominated by radiation (Antiochos 1980). McTiernan et al. (1993) find that the long flare decay times are incompatible with significant conduction, and that radiation is the dominant cooling mechanism.

The rate of change of the total thermal energy E in a plasma of volume V with electron density n is determined by the influx of kinetic energy and by radiation, hence the energy conservation equation for the *thermal* plasma

$$\frac{d}{dt}(3nkTV) = \alpha F_R(t) - n^2 V \psi(T) \quad (1)$$

where $\psi(T)$ is the total luminosity of a plasma with unit emission measure (EM) at a temperature of T . Note again that equation (1) does, by definition of α , not describe the total energy budget of the flare, but merely the energy conversion of interest here. For large flare temperatures ($\gg 20$ MK), ψ is dominated by bremsstrahlung losses, roughly scaling as $T^{1/2}$. For detailed expressions, see Mewe, Gronenschild, & van den Oord (1985) and Landini & Monsignori-Fossi (1990). For somewhat more moderate temperatures ($\gtrsim 10 - 20$ MK), losses via line emission become important, with the (isothermal) approximation for ψ

$$\psi(T) = 1.86 \cdot 10^{-25} T^{1/4} [\text{erg s}^{-1} \text{ cm}^3] \quad (2)$$

(van den Oord & Mewe 1989). In the absence of kinetic energy influx $\alpha F_R(t)$, the thermal energy decays radiatively (neglecting conduction), and hence we define an e-folding decay time τ for the thermal energy as a function of the two independent variables temperature T and density n at a given instant,

$$\left. \frac{dE}{dt}(t) \right|_{F_R=0} = \frac{E(t)}{\tau(n(t), T(t))} \quad (3)$$

so that

$$\tau(n(t), T(t)) = \frac{E(t)}{L(t)} = \frac{3kT}{n\psi(T)} \quad (4)$$

where L is the total luminosity. Then,

$$\frac{dE}{dt}(t) = \alpha F_R(t) - L(t) = \alpha F_R(t) - \frac{E(t)}{\tau(t)}. \quad (5)$$

The general solution of the inhomogeneous, linear differential equation (5) reads

$$E(t) = e^{-\int_{t_0}^t \tau(y)^{-1} dy} \left(E_0 + \alpha \int_{t_0}^t F_R(u) e^{+\int_{t_0}^u \tau(y)^{-1} dy} du \right) \quad (6)$$

where $E_0 = E(t_0)$ for a fixed t_0 before the flare start. The integration over τ^{-1} is along the time axis. If the initial thermal energy content can be neglected ($E_0 = 0$), then

$$E(t) = \alpha \int_{t_0}^t F_R(u) e^{-\int_u^t \tau(y)^{-1} dy} du. \quad (7)$$

We define an average decay constant for any time interval $[u, t]$ by

$$\bar{\tau}^{-1} = \bar{\tau}^{-1}(u, t) = \frac{\int_u^t \tau(y)^{-1} dy}{t - u}. \quad (8)$$

Then

$$E(t) = \alpha \int_{t_0}^t F_R(u) e^{-(t-u)/\bar{\tau}(t,u)} du, \quad (9)$$

i.e., for constant τ the energy profile is the *convolution* of the kinetic energy influx with an exponential function. We refer to equation (9) as the *generalized Neupert effect*. In the limit $\tau \rightarrow \infty$, equations (5) and (9) become

$$\frac{dE}{dt}(t) = \alpha F_R(t) \quad (10)$$

$$E(t) = \alpha \int_{t_0}^t F_R(u) du, \quad (11)$$

i.e., the total energy content of the plasma is the integral of the kinetic energy influx (and radiation is inhibited; equation 10 is consistent with the strong evaporation limit in Fisher & Hawley 1990). Equations (10) and (11) remind us of the classical formulation of the Neupert effect, with the observed X-ray losses replaced by the thermal energy content in the plasma. These two equations are applicable only for the increasing portion of the soft X-ray light curve or, correspondingly, for

the time interval where $F_R \neq 0$. On using equation (4), we obtain the *generalized Neupert effect for the light curve*,

$$L(t) = \frac{\alpha}{\tau(t)} \int_{t_0}^t F_R(u) e^{-(t-u)/\tau(t,u)} du. \quad (12)$$

Note the importance of the thermal *energy* decay parameter $\tau = 3kT/(n\psi(T))$. Serio et al. (1991) and Jakimiec et al. (1992) find $Tn^{-2} = \text{const}$ for the radiative cooling phase. If the temperatures are very high and the bremsstrahlung approximation applies, then $\tau = T^{1/2}n^{-1}$ and thus $\tau = \text{const}$ in equation (12). However, in the case of more moderate temperatures (eq. 2), only for $T^{3/4}n^{-1} = \text{const}$ does the classical Neupert effect approximately apply to the light curve. The actual functional dependence of $\psi(T)$ is more complicated. Thus, in general, the relevant parameters to be investigated for the Neupert effect are the *energies*. This was also pointed out in a study by Lee, Petrosian, & McTiernan (1995) who find incompatibility between a statistical sample of flares and the simple formulation of the Neupert effect. Further, $L(t)$ describes all radiative losses across the electromagnetic spectrum; the observed X-ray luminosity L_X generally depends on the selected bandpass and therefore constitutes only a lower limit to L .

If we know $T(t)$ and $\text{EM}(t)$ from observations (Benz & Güdel 1994 for solar flares), we use the result from equations (6), (7), or (9) to obtain

$$N(t) = \frac{E(t)}{3kT(t)}, \quad (13)$$

$$n(t) = \frac{\text{EM}(t)}{N(t)}, \quad (14)$$

$$V(t) = \frac{N(t)}{n(t)}, \quad (15)$$

where $N = nV$ is the total number of electrons in the X-ray emitting plasma.

4.2. On the Neupert effect in solar flares

From the simple derivation in the previous section, the Neupert effect is not expected to strictly manifest itself in the observed X-ray luminosity, since amplitude, shape, and peak time of the L_X light curve are functions of T , n , and the observing bandpass. Equations (9)–(15) can, on the other hand, be used to explore the *conditions* required for the observed relative timing (peak delays, increase, etc.) between the radio and X-ray flare events *if* operation of the simplified chromospheric evaporation model outlined in Sect. 4.1 is assumed to be valid.

Solar flares reveal an amazing complexity in their structure and development, with different events showing their unique peculiarities (see the review by Wu et al. 1986 and references therein). We are considering only the most important effects and can therefore not claim considerable quantitative accuracy here (in particular due to the neglect of possible supplementary direct heating and conductive losses during the first phase of the flare, as well as a possible time dependence of

α). Comparison with more sophisticated observations of all important forms of energy deposition (e.g., Antonucci et al. 1984; Antonucci et al. 1993; see also Wu et al. 1986) shows qualitative agreement.

We extrapolated the observed L_X by modeling into the 0.01–50 keV energy range instead of using the empirical formula (2) for the total radiative losses of the hot plasma. We then integrated equation (5) (or eq. [7]) and applied equations (13)–(15) to derive n , N , and V from the modeled E and the observed EM and T . We emphasize that E is the only modeled parameter in the simple chromospheric evaporation scenario proposed here. The other quantities are then directly implied by the observed EM, T , and $\int F_R dt$ histories. The unknown but constant conversion factor α is adjusted such that, *after the radio flare*, the thermal flare energy is gradually radiated away (i.e., no rapid energy collapse due to radiation), and V , n , and N no longer significantly increase.

We show in Figure 5a the results for the solar gradual flare observed on 1981 April 26 that was discussed by Cliver et al. (1986), Dennis & Zarro (1993), and Benz & Güdel (1994). “Gradual flares” (Cliver et al. 1986, also called “type C flares” and to be distinguished from the “gradual phase” of solar flares, Wu et al. 1986) define a class of solar flares with very long HXR time scales, continuous hardening of the HXR emission along the complete flare, and an efficient production of microwave radiation. The flare in Figures 5a,b consists of an impulsive precursor at 11:20 UT (with components in radio and X-rays, see Fig. 5b), and the long, gradual flare of interest here. We subtracted the precursor after extrapolating its decay. All time histories are normalized by powers of ten to a common scale. The unit for the radio flux density is 1 SFU = 10^{-19} erg s $^{-1}$ cm $^{-2}$ Hz $^{-1}$ (solar flux unit).

The *measured* electron temperature rises rapidly during the initial bombardment (in the evaporation scenario) of the chromosphere to a maximum shortly after the microwave peak, and then decays gradually. The emission measure, on the other hand, develops more gradually during the evaporation phase, and consequently, the *derived* electron density reaches its peak with a considerable delay. During the initial hot phase, a significant part of the X-ray luminosity is radiated into harder portions of the soft X-ray band. This emission decays rapidly as the temperature decreases. In contrast, softer bands are less temperature sensitive, and their X-ray luminosities correlate well with the total (temperature-integrated) volume emission measure. The resulting successively larger delays of softer energy bands are illustrated in Figure 5b. The three X-ray light curves (thin solid lines) were observed by a GOES satellite and refer to the harder GOES bandpass (3–24 keV), the softer GOES bandpass (1.5–12 keV), and a modeling into the ROSAT bandpass (0.1–2.4 keV, also shown in Fig. 5a) based on temperature and emission measure analysis of the two GOES channels (Benz & Güdel 1994). The light curves have been renormalized to the same peak amplitude for illustration purposes; the effective amplitudes can be found in Benz & Güdel (1994).

The thick solid line in Figure 5b refers to the convolution of the radio curve with an exponential function (eq. 12), using a constant τ to approximately fit the late X-ray flare decay (55 minutes in this example; larger τ shift the peak only by a small amount to later times, but the flare decay will be in considerable disagreement with the observations). The best match is found with the hardest

X-ray light curve (peak delay of 10 minutes), while it is worst for the softest (peak delay of 65 minutes). We experimented with derivatives of the soft X-ray light curves also; their time delays were, for decreasing hardness, 6, 11, and 51 minutes. Using the harder GOES channel, we find, in contrast to Dennis & Zarro (1993), that the Neupert effect is rather well established. However, Dennis & Zarro used the derivative of the soft GOES channel only. This example illustrates that the flare conditions (T, n) essentially determine to what extent and in which soft X-ray band the Neupert effect is best observable (see eq. 12). Similar trends were found for a number of impulsive and gradual flares.

The energy conversion factor α that leads to the required convergence of all light curves is $(4.5 \pm 0.1) \cdot 10^{24}$ erg s⁻¹ per SFU in this example, i.e., $1.6 \cdot 10^{-16}$ erg of kinetic energy for each radiated erg Hz⁻¹ in the microwave domain. Assuming an effective bandwidth of 20 GHz, a fraction of $\sim 10^{-6}$ of the initial energy is radiated as gyrosynchrotron emission. If α is smaller, too little energy is deposited in the plasma so that the observed X-ray luminosity cannot be maintained; larger rates lead to a divergent number of thermal electrons or a divergent volume after the radio flare. We found similar conversion factors for about ten other solar flares investigated with the same method.

The total energy in Figure 5a reaches a maximum of $3 \cdot 10^{31}$ erg when the radio light curve has dropped to 10% of its peak flux, and then slowly decays due to radiative cooling. Of this, a total of $1.8 \cdot 10^{31}$ erg or 60% is radiated into soft X-rays.⁴

4.3. Chromospheric evaporation in UV Ceti

We now apply the *solar analogy* to our observations to discuss the relevance of chromospheric evaporation on UV Ceti. We cannot directly apply our modeling in Sect. 4.1 to the UV Ceti flares because the temperature and the emission measure time histories are not explicitly known. Figure 6 displays the solar event on 1981 April 26 (upper panel, modeled into the 0.1–2.4 keV bandpass) together with UV Ceti flare *D* and the accompanying X-ray emission (the amplitude calibration will be discussed in the next section). We obtained the radio light curve precisely from the position of UV Ceti A (rather than UV Ceti B as in Fig. 1). Solar fluxes have been converted to a distance of 2.6 pc. The relative scaling between radio and X-ray fluxes is the same in both panels, but note the difference in the absolute scaling for the two flares. The similarity in the timing (start times

⁴The maximum density of $1.8 \cdot 10^{10}$ cm⁻³ is modest compared with other flares; typically, $n \gtrsim 10^{11}$ cm⁻³ (e.g., Antonucci et al. 1984). Using the same simple algorithm for several other flares, we indeed find typical peak densities during the evaporation phase of several times 10^{11} cm⁻³; we therefore believe that the extraordinarily low n is real in this flare. Note the very long decay time in this context: We determined a cooling rate per unit emission measure at 8 MK of $\psi(8 \text{ MK}) = 3 \cdot 10^{-23}$ erg s⁻¹cm³ from the MEKA model in XSPEC, using the formal limits of 0.01 keV and 50 keV. Since $n \approx 1.8 \cdot 10^{10}$ cm⁻³ at the peak of the EM, we find from equation (4) $\tau = 6200$ s, in very good agreement with the decay time of the energy (note that T and n continuously modify τ).

and peak delays) between the radio and the soft X-ray emissions is striking. As shown above for the solar event, we cannot expect to observe a detailed “Neupert” behavior for the stellar flare in this softest band, but since such appears to hold for the harder GOES channel for solar flares, we conclude that *a very similar mechanism of energy deposition is at work in the stellar chromosphere*. The much noisier data set for UV Ceti flare *A* reveals a similar picture (Fig. 3).

Both at 3:30 UT on day 1 and at 6:30–7:10 UT on day 2, the harder radiation develops significantly faster than the soft emission (note the hardness ratios in Figs. 1 and 4; peak delays are 5 min and at least 20 min, respectively). The hardening early in the flare and the softening already before the soft X-ray peak imply a rapid heating to peak temperatures early in the flare. This picture is also fully analogous to the solar case (Figs. 5a,b). A similar behavior has been reported for other dMe star X-ray flares; Haisch et al. (1987) found delays of about 1000 s in a 1 hr flare on the dMe star EQ Peg, using similar energy intervals. Doyle et al. (1988) reported a 80 s delay in a 20 minute flare on Gliese 644AB.

We conclude that chromospheric evaporation is the likely explanation for the behavior observed in UV Ceti (and perhaps in other flare stars), in analogy to the Sun. The considerable time delays and the hardness development of the X-ray emission naturally ensue from a rapid increase and subsequent decay of the temperature during the evaporation phase, accompanied by a more gradual development of the density and, hence, the emission measure. This scheme is in full agreement with many other solar observations (Fig. 5a; Antonucci et al. 1984; Wu et al. 1986).

Effects of chromospheric evaporation are not always observable in solar flares. In particular, series of flares may quench the operation of chromospheric evaporation. After initial evaporation, the density in the coronal loops becomes sufficiently high to inhibit further bombardment of the chromospheric layers. Subsequent energetic electrons then thermalize at higher coronal levels, thus leaving the number of radiating particles essentially constant. The new energy will merely increase the temperature, but this does not increase the flare plasma luminosity (in the regime $\lesssim 30$ MK). Rather, the flare decay is slowed. Such effects have been found in double impulsive *solar* flares in which the second event reveals absence of mass motion by chromospheric evaporation but instead peaks at higher temperatures (Strong et al. 1984). This may also be a viable scenario for UV Ceti flares *A/B/C* in view of the very slow decay of the X-ray flare at 3:30 UT. While flare *A* is accompanied by an X-ray flare increase as expected from the chromospheric evaporation scenario, flare *B* appears to induce an increase of X-ray hardness on top of the gradual X-ray flare, compatible with a rise of the temperature. During the radio flare *C* the X-ray light curve shows a plateau with constant HRI count rate, followed by a drop. Alternatives to the quenching scenario for flare *C* are also possible, e.g., a lowered efficiency of nonthermal energy conversion, or partial invisibility of the X-ray source due to its location behind the stellar limb, while the radio radiation is emitted from higher loops.

4.4. Flare energetics

4.4.1. Radiated energies

From the spectral fits to the flare sections, we derive a count rate to (0.1–2.4 keV) luminosity conversion factor of $2.1 \cdot 10^{28}$ erg s^{−1} per SIS ct s^{−1}; this corresponds to a measured energy flux at Earth of $2.5 \cdot 10^{-11}$ erg s^{−1}cm^{−2} for each SIS ct s^{−1}. This allows us to estimate peak luminosities of flares and, using their FWHM durations, the total radiated X-ray energies. Analogously, we determined radio flare peaks and total spectral energies for the corresponding radio flares. The results for the UV Ceti flares are presented in Table 3, together with the values for the gradual solar event discussed above. As estimated in Sect. 3.3, systematic errors in the peak L_X introduced by the unknown run of T and statistical errors in the fits amount to less than 20%. An error of 10–20% is estimated for uncertainties in the time integration for flares A and D , and up to 50% for the smaller flare a .

Comparing the energetics of the solar and the UV Ceti flares, we notice the following important points: i) The ratios between flare durations in X-rays and radio are similar for the stellar and the solar flares (8.1 ± 2.6). ii) The UV Ceti flare D is stronger at its peak than the solar flare by a factor of 6.6 in radio and a factor of 2.7 in X-rays despite its shorter duration in both wavelength regimes (factor of ~ 1.7). iii) The ratios between the the peak X-ray and radio luminosities of the stellar gradual flares A and D are considerably smaller than in the case of the solar gradual flare. The stellar flares are “radio-overluminous”. iv) For the total released energy of the stellar gradual flares A and D , we get $E_X/E_R \approx (2.2 - 3.4) \cdot 10^{15}$ Hz. For the solar flare, $E_X/E_R \approx 6.0 \cdot 10^{15}$ Hz.

We previously found that solar flares are more efficient in the production of X-ray energy than the quiescent coronae of active stars if normalized to the corresponding emission in microwaves (Benz & Güdel 1994), with $\log(E_X/E_R) \approx 16.3$ and a scatter of 0.26 dex around the least-squares regression line for 16 impulsive and gradual flares (the gradual solar flare considered above is the most X-ray deficient among the large flares in the sample). Here, we see that the stellar flares produce less X-ray emission than a comparable solar flare when normalized with the radio energy output. As a consequence, we now find that *the stellar flare energy ratio E_X/E_R closely matches the time averaged quiescent stellar luminosity ratio $L_X/L_R \approx 3 \cdot 10^{15}$ Hz* (with a typical scatter of a factor of 2–3; Güdel & Benz 1993).

One could argue here that higher stellar flare temperatures imply a more moderate X-ray radiation at the peak, while the energy budget of the flare remains comparable. A 3 keV plasma indeed radiates 1.9 times less intensely in the [0.1,2.4] keV range than a 0.8 keV plasma (the solar flare at its peak). In our spectral fit to the UV Ceti flare data, however, only 43% of the flare plasma is found at very high temperatures, thus accounting for a relative X-ray deficiency of only 20%. Better temperature (and elemental abundance) determinations of the stellar flare plasma are needed to estimate the effect on L_X . Further, it does not explain the deficiency in the total radiated energy unless additional, non-X-ray losses play a key role. Another cause for the observed

difference may lie in the distribution of nonthermal electrons. In the thick-target model for a power-law distribution of fast electrons (with $\gamma \geq 2$), the plasma derives its thermal energy mainly from the lowest-energy electrons, while microwaves are emitted by the mildly relativistic high-energy portion. Differences in the power-law index γ or broken power-laws can be important. Further, higher average magnetic field strengths in the emitting region on UV Ceti will require lower-energy electrons for the observed emission; thus, more electrons will radiate (cf., Dulk & Marsh 1982). Component B of the UV Ceti system has been found to be “radio-strong” with regard to its X-ray level (Güdel et al. 1993); we can only speculate whether sequences of radio flares that occur during a large X-ray event like flares A/B/C are, combined with quenching of chromospheric evaporation and increased losses into other channels, responsible for the X-ray deficiency.

4.4.2. The total energy in the thermal plasma

We will now derive the energy budget for the observed radio and X-ray flares, and will again use knowledge from solar soft X-ray, HXR, and radio observations. The nonthermal hard X-ray photon flux spectra ($\sim 20 - 100$ keV) of solar flares are usually described in terms of a power law

$$\mathcal{F}_{\text{HXR}}(\epsilon) = C\epsilon^{-\gamma} \quad [\text{ph cm}^{-2}\text{s}^{-1}\text{keV}^{-1}] \quad (16)$$

where $\mathcal{F}_{\text{HXR}}(\epsilon)$ is the differential flux of photons at energy ϵ , and the power-law index γ for photons typically ranges between 3 and 4 for gradual flares (Dennis 1985; Cliver et al. 1986). C is a constant determined from the observations. The total count rate above the limiting lower threshold energy ϵ_0 thus becomes

$$F_{\text{HXR}} = \int_{\epsilon_0}^{\infty} A_{\text{eff}}(\epsilon) \mathcal{F}_{\text{HXR}}(\epsilon) d\epsilon \approx \frac{\bar{A}_{\text{eff}} C}{\gamma - 1} \epsilon_0^{-\gamma+1} \quad [\text{cts s}^{-1}]. \quad (17)$$

(Eq. (17) requires $\gamma > 1$.) The parameter $A_{\text{eff}}(\epsilon)$ is the effective area of the detector; for the SMM HXRBS used here for solar observations, $\bar{A}_{\text{eff}} \approx 40 \text{ cm}^2$. From the theory of thick-target bremsstrahlung (Brown 1971), the differential electron flux $\mathcal{F}_e$ into the chromosphere is related to the photon spectrum, with

$$\mathcal{F}_e(\epsilon) = \frac{1.39 \cdot 10^{44}}{\pi r^2} d_{\text{pc}}^2 b(\gamma) C \epsilon^{-\gamma-1} \quad [\text{electrons cm}^{-2}\text{s}^{-1}\text{keV}^{-1}] \quad (18)$$

(generalized from Hudson et al. 1978) where d_{pc}^2 is the source distance in pc, and πr^2 is the target source area. The total “nonthermal” power being deposited in the chromosphere is

$$P_e = \int_{\text{target}} \int_{\epsilon_1}^{\infty} \epsilon \mathcal{F}_e(\epsilon) d\epsilon dA = \frac{1.39 \cdot 10^{44} d_{\text{pc}}^2 b(\gamma) C}{\gamma - 1} \epsilon_1^{-\gamma+1} \quad [\text{keV s}^{-1}]. \quad (19)$$

Here, $b(\gamma) = \gamma^2(\gamma-1)^2\Gamma(\gamma-1/2)\Gamma(3/2)/\Gamma(\gamma+1)$, with Γ being the gamma function. For $3 \leq \gamma \leq 6$, $b(\gamma) \approx 2^\gamma$ is a sufficiently accurate approximation (within $\pm 11\%$). Note that we use a different lower threshold ϵ_1 for the electrons. Again, $\gamma > 1$ is required for convergence. From observations

using the SMM HXRBS, a statistical relation holds for solar *gradual* flares between the peak count rate of HXR and the peak flux in radio (Kosugi et al. 1988; Cliver et al. 1986), with

$$F_{\text{HXR,HXRBS}} \approx 10^{19} F_{\text{R}} \quad [\text{cts s}^{-1}] \quad (20)$$

where F_{R} is in $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$. The ratio between HXR count rate and microwave flux is about ten times larger for impulsive flares (Cliver et al. 1986). With equations (17), (19), and (20), we obtain (after conversion to erg and mJy)

$$P_e \approx 5.6 \cdot 10^{26} 2^\gamma \left(\frac{\epsilon_1}{\epsilon_0} \right)^{1-\gamma} \left(\frac{F_{\text{R}}}{1 \text{ mJy}} \right) \left(\frac{d}{1 \text{ pc}} \right)^2 \quad [\text{erg s}^{-1}]. \quad (21)$$

We will set $\epsilon_0 = \epsilon_1 = 25 \text{ keV}$ henceforth. For the stellar flares, the power-law index γ is unknown. From spectral observations of *quiescent* stellar radio emission and flares on active RS CVn binaries, power-law indices of $\gamma \approx 3 - 4$ are derived for the high-energy tail of electrons (e.g., Güdel 1994 and references therein). From the analogy of the observed flares with solar gradual events, we suggest that $3 \lesssim \gamma \lesssim 4$ is reasonable for the stellar flares. The overall similarity between the stellar flares *A* and *D* with solar gradual flares suggests similar operation of the electron acceleration processes. Lacking any observed hard X-ray emission from dMe stars, we suggest that equation (20) would be applicable also for stellar events. Using $F_{\text{R}} = 1.9 \text{ mJy}$ and 1.3 mJy for flares *D* and *A*, respectively, and multiplying P_e with the durations from Table 3, we obtain a total nonthermal kinetic energy in the electrons of $4.4 \cdot 10^{31} - 8.8 \cdot 10^{31} \text{ erg}$ for flare *D* and $1.8 \cdot 10^{31} - 3.6 \cdot 10^{31} \text{ erg}$ for flare *A* ($\gamma = 3 - 4$). For the solar flare (with a peak flux of 0.28 mJy at UV Ceti’s distance), we obtain $1.1 \cdot 10^{31} - 2.2 \cdot 10^{31} \text{ erg}$. Relating these numbers to the total emitted soft X-ray energies in Table 3, we observe that the nonthermal energy is between 1.1 (for $\gamma = 3$) and 3.3 (for $\gamma = 4$) times higher than the radiated thermal energy. This disparity can be alleviated by raising the lower energy threshold for the heating nonthermal electrons. There is, however, more reason to assume that the power-law tail continues to even lower energies, possibly down to a few keV (Wu et al. 1986), thus aggravating the discrepancy further. For the solar flare, the corresponding ratios between nonthermal and thermal energies are about one half of those for the stellar flares, viz. 0.6–1.2. In the case of solar flares, the dominance of the nonthermal electron energy is well-known but defies a definite explanation (Wu et al. 1986).

If the initial energy predominantly resides in fast particles, we should indeed expect that only part of it is radiated in soft X-rays. The remaining energy is transformed, for example, into mechanical energy in the evaporation process, and a considerable portion will heat dense material in the chromosphere to moderate temperatures only; this plasma will emit its bulk radiation in the optical continuum and in optical lines. As a matter of fact, stellar flares on dMe stars emit a high percentage of their energy in the optical continuum and in Balmer lines (Doyle & Butler 1985; Bastian 1990). This could be yet another cause for the observed relative weakness of the X-ray luminosity (with respect to the radio luminosity) of the stellar flares. Multiwavelength studies including optical, ultraviolet, X-ray, and radio observations are needed to obtain better energy budgets for the complete flaring atmosphere and to estimate the most significant energy losses. For optical, UV, and X-ray work on the flare energy budget, see Hawley & Pettersen (1991).

5. Conclusions

Chromospheric evaporation through energy deposition by energetic electrons accelerated in the corona is by now a well accepted scenario that may be relevant for many *solar* flares. In our observations of UV Ceti, we found several radio bursts that resemble microwave gyrosynchrotron bursts during solar gradual flares in their amplitude, duration, shape, and polarization. At least two, and perhaps four, of the radio bursts are characteristically followed by X-ray flares. By studying a solar flare with very similar overall characteristics, we infer that analogous mechanisms are at work both in the stellar and in the solar gradual flares. We argue that the Neupert effect in its classical formulation, i.e., as a correlation between the X-ray curve and the time integral of the radio curve, is not necessarily expected in stellar observations; reasons include: i) chromospheric evaporation operates such that the Neupert effect is found in the energy balance rather than in the radiative losses; ii) the source conditions, i.e., T and n , largely determine the evolution of the observable radiation; and iii) the selected energy bandpass determines shape and timing of the X-ray light curve. A generalized Neupert effect formulation including the thermal energy decay time scale is needed for a proper description of chromospheric evaporation. Cooling effects can induce delays between light curves in different energy bands of the thermal X-ray regime (up to many keV) that should not themselves be mistaken for a Neupert-effect (see Fig. 5); we have avoided this complication by using observations of definitely nonthermal microwaves emitted by relativistic electrons. We applied a simplified scheme to infer the time histories of the source parameters that eventually induce a Neupert effect-like behavior during chromospheric evaporation. Comparing the radio/X-ray pairs found on UV Ceti with a typical solar gradual flare, we find a compelling similarity in terms of relative timing, duration, and total energies in all cases. We conclude that UV Ceti’s flares are subject to processes similar to those in solar gradual flares, and that chromospheric evaporation is the most straightforward explanation for this behavior.

The observations thus provide evidence that, like in the Sun, electrons with energies between 10 keV and several 100 keV are amply present in stellar coronae and connect to the higher energy electrons directly observable in microwaves. Undoubtedly, these medium-energy electrons are the source of HXR radiation as in solar flares. The interpretation of our observations in terms of chromospheric evaporation not only implies that the thermal, the medium-energy nonthermal, and the high-energy microwave emitting electrons are related in flares but that their populations are *causally related* in the type of stellar flares observed here. In one case, we found possible evidence of quenching of chromospheric evaporation. The coronal loop density appears to have sufficiently increased by the initial evaporation to effectively suppress further precipitation of energetic electrons to the chromosphere. The emission measure does consequently not increase, but since the electrons deposit their energy at coronal heights, they simply increase the coronal plasma temperature, and this is confirmed by increasing hardness ratios in the soft X-rays just following the second radio flare.

Different from solar flares, however, we find that the stellar flares produce more radio emission per emitted X-ray radiation, suggesting a lower efficiency of the X-ray emission. We identified four

possible causes: i) Higher flare temperatures result in a lower peak luminosity in the observed bandpasses used for stellar soft X-ray observations. ii) Losses into other wavelength bands, e.g., the optical continuum and Balmer lines, or non-radiative losses could play a more important role in stellar flares. This is particularly the case if the precipitating energy heats a large volume of plasma in the lower chromosphere to modest temperatures only, inducing radiative losses mainly in the ultraviolet and optical regimes. The loop geometries are thus important for the heating efficiency. iii) Average magnetic fields in the microwave emitting regions are higher, employing lower-energy (and thus more numerous) electrons for the radio radiation at a given frequency. iv) The distribution of fast electrons could be different in the average stellar flare, containing a larger fraction of microwave emitting relativistic electrons.

From the observed radiative energy losses, the stellar flares behave similar to the quiescent radio and X-ray radiation from active dMe stars (which also show very hot temperatures that exceed solar flare temperatures). Perhaps similar mechanisms are at work in the quiescent and in the flaring radiation. We have found several flares in the dMe star UV Ceti that are relatively modest in amplitude and appear to be present during a considerable time at least during our observing intervals. The possibility that much of the quiescent radiation is, apart from a possible basal level as in the solar case, due to numerous small-scale flares needs further investigation.

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Table 1. UT observing times

Day	ASCA	ROSAT	VLA
January 5–6	15:13–07:58	15:44–06:20	21:35–06:07
January 6–7	15:09–07:58	15:36–06:12	21:21–06:02

Table 2. Candidates for the Neupert Effect

Radio flare peak (UT hrs)	Coincident X-ray flare (UT hrs)	Neupert Effect? Comments
<i>day 1 (January 5-6)</i>		
1:15 ('a')	1:30	possible candidate
3:50 ('b')	~3:30 (gap)	gyrosynchrotron unlikely; X-ray gap
<i>day 2 (January 6-7)</i>		
21:40	21:50	X-ray increase unobserved; more significant in RCP
23:05	(Earth block)	X-ray decrease at >23:20
00:30-01:20	(Earth block)	X-ray decrease at 1:05
2:40 ('A')	~3:20	candidate
3:15 ('B')	3:20	candidate , hardness increase
4:20 ('C')	absent?	no
5:30 ('D')	6:50	candidate

Table 3. Flare luminosities and radiated energies

	$\log(L_{\text{peak}})$ ($\text{erg s}^{-1}[\text{Hz}^{-1}]$) ^a	$\log(E_{\text{tot}})$ ($\text{erg}[\text{Hz}^{-1}]$) ^a	Duration (s)
Flare <i>a</i> : X-ray ^b	27.26	30.39	1360
Flare <i>a</i> : radio	12.86	15.11	180
Flare <i>a</i> : X-ray/radio	14.40	15.28	7.6
Flare <i>A</i> : X-ray ^b	27.53	31.22	4900
Flare <i>A</i> : radio	13.03	15.69 ^d	460
Flare <i>A</i> : X-ray/radio	14.50	15.53 ^d	10.7
Flare <i>D</i> : X-ray ^b	27.80	31.43	4300
Flare <i>D</i> : radio	13.18	16.08	770
Flare <i>D</i> : X-ray/radio	14.62	15.35	5.6
Sun: 81/04/26 X-ray ^b	27.3	31.25	7580
Sun: 81/04/26 radio ^c	12.36	15.48	1300
Sun: 81/04/26 X-ray/radio	15.01	15.77	5.8

^aUnits in brackets are relevant for radio emission only.

^bEnergy range for soft X-rays: [0.1,2.4] keV.

^cRadio peak flux density from Cliver et al. 1986.

^dIf flare *B* is added ($\log E_{\text{tot,R,B}} = 15.26$), then $\log E_{\text{tot,R}} = 15.83$ and $\log(E_{\text{tot,X}}/E_{\text{tot,R}}) = 15.39$.

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Fig. 1.— Light curves from the observing campaign on January 5/6, 1995. The panels show, from top to bottom: (i) VLA radio light curve at 6 cm wavelength, binned to 60 s (lower curve) and to 300 s (upper curve, shifted by +3 mJy along the flux axis). (ii) The circular polarization degree of flare-like enhancements in the radio light curve; concentrations of weakly polarized bins are bracketed by vertical lines. (iii) The GIS (error bars) and adjusted HRI (diamonds with error bars) light curves, binned to 128 s. (iv) The SIS (error bars) and adjusted HRI (diamonds with error bars) light curves, binned to 128 s; the insets with 256 s bin width are light curves containing photons with energies between 2 and 10 keV only. (v) The spectral hardness of the SIS light curve. See text for details.

Fig. 2.— As Fig. 1, for the observing campaign on January 6/7, 1995. Radio observations were obtained at 3.6 cm wavelength.

Fig. 3.— Radio and X-ray light curves of UV Ceti flares *A*, *B*, and *C* on day 2. *Upper panel*: Radio light curve, binned to 90 s. *Middle panel*: X-ray light curves from the HRI detector (bullets), and from the SIS detectors between 0.5–2 keV (crosses) and between 2–10 keV (diamonds), binned to 256 s. The HRI count rate has been adjusted to the SIS level. *Lower panel*: SIS hardness (2–10 keV count rate to 0.5–2 keV count rate).

Fig. 4.— Similar to Fig. 3, for flare *D* on day 2. Radio data are binned to 150 s.

Fig. 5.— **a)** (*Top*) Modeling of the flare parameters in the 1981 April 26 solar event, assuming a simplified chromospheric evaporation model. The radio burst (observed at Sagamore Hill, data from Solar Geophysical Data) is shown by a thick solid curve. The X-ray light curve L_X refers to the 0.1–2.4 keV bandpass (as modeled from GOES data). Temperatures T and emission measures EM were derived from the GOES “hardness ratios”. Derivation of the flare source parameters volume (V), thermal electron density (n), number of hot thermal electrons in the source (N), and thermal energy deposited by fast electrons (E) is described in the text. The subscripts to the symbols denote the power of ten by which the original values have been divided. **b)** (*Bottom*) Evidence for the Neupert effect in the solar flare of 1981 April 26. The flare consists of an impulsive phase at 11:15 UT, and a gradual event after 12:30 UT. Dotted: The radio burst. Thin solid curves: The X-ray event in three soft X-ray bands; from left to right: GOES 3–24 keV bandpass; GOES 1.5–12 keV bandpass; 0.1–2.4 keV band modeled from the harder GOES channels. Thick solid curve: Convolution of the radio event with an exponential function, using a decay time constant of 55 minutes. The X-ray curves have been renormalized to the same peak amplitude. Note the close similarity between the convolved radio light curve and the *harder* GOES light curve, but increasing discrepancy with decreasing X-ray photon energy.

Fig. 6.— Comparison of the UV Ceti flare on 1995 January 7, 7 UT (bottom panel), with the solar gradual event on 1981 April 26 (top panel). *Thin curves*: Radio burst; *thick curves*: X-ray flare. The stellar X-ray and radio curves are smoothed (radio: boxcar with a width of 3 bins of 256 s each; X-ray: smooth cubic spline approximation). The error bars on the right side of the lower

panel are representative for the individual data points during the flare (VLA 150 s bins and and SIS 256 s bins). The solar fluxes have been converted to UV Ceti's distance. The scales on the time axis and the relative flux scales are the same for both panels. Note, however, that the solar flare fluxes are considerably smaller. Relative to the X-rays, the stellar flares produce larger radio amplitudes than the solar analog.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6