THE NEUPERT EFFECT IN σ GEMINORUM

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Abstract

The RS CVn-type binary σ Geminorum was observed during a large, long-duration flare simultaneously with XMM-Newton and the VLA. The light curves show a characteristic time dependence that is compatible with the Neupert effect observed in solar flares - the time derivative of the X-ray light curve resembles the radio light curve. This observation can be interpreted in terms of a standard flare scenario in which accelerated coronal electrons reach the chromosphere where they heat the cool plasma and induce chromospheric evaporation. Such a scenario can only hold if the amount of energy in the fast electrons is sufficient to explain the X-ray radiative losses. We present a plausibility analysis that supports the chromospheric evaporation model.

Key words: Flare stars, Chromospheric evaporation

1. Introduction

A standard solar flare scenario proposes that electrons (perhaps also ions) are accelerated in the corona in the course of magnetic reconnection. As the electrons travel along closed magnetic fields, those with large pitch angles and sufficient energy lose a small part of their energy as gyrosynchrotron radio emission. The bulk kinetic energy of the accelerated electrons, however, is carried to the chromosphere where it is deposited by electron-ion collisions. The collision of the beam with the dense plasma reveals itself by non-thermal hard X-ray radiation (HXR, typically between 10−100 keV) that, however, constitutes only a small fraction of the total energy. The bulk energy is transformed to heat, producing an overpressure in the chromosphere as the gas cannot radiate the energy influx sufficiently rapidly. As a consequence, the gas evaporates explosively into the corona as $\sim 10^7$ K plasma visible in X-rays during the gradual phase of a solar flare (Dennis 1988).

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$$L_{\rm R}(t) \propto \frac{d}{dt} L_{\rm X}(t),$$

a relation that is commonly known as the 'Neupert Effect' (Neupert, 1968). For solar flares, the left-hand side of the above equation can be replaced by the HXR luminosity, $L_{\rm HXR}$.

It is thought that the same mechanisms should operate in stellar flares, although flares on some classes of stars deviate considerably from the proposed solar analogy. In particular, giant flares on RS CVn-type binaries may require mechanisms unknown on the Sun. RS CVn binaries, commonly consisting of a giant or subgiant primary with a main-sequence or subgiant companion in a close orbit, are sources of luminous radio and X-ray emission (Drake, Simon & Linsky, 1989). Very long flare time scales and radio source sizes of order of the intrabinary distance have been modeled in terms of giant dipole-like magnetospheric structures (Morris, Mutel & Su 1990; Jones et al 1994) into which high-energy particles are injected from a flare site, and where they lose most of their energy by radiation. Coordinated observations in X-rays and radio are required to study the importance of high-energy electrons in the heating mechanism.

2. The σ Gem event

Motivated by Equation 1, we boxcar smoothed the X-ray light curve and calculated the time derivative. The result is illustrated in Figure 1, and is to be compared with the radio light curve in the lower panel. Figure 1 shows compelling evidence for the presence of a Neupert effect, i.e., a radio light curve that is approximately proportional to the time derivative of the X-ray light curve. Note that the units of the X-ray time derivative and the radio flux are not important for this relation and the figures have been scaled arbitrarily. The light curves alone do not prove the operation of chromospheric evaporation induced by electron beams. It is possible that the rate of electron injection is proportional to the rate of heating,

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both being induced by the same mechanism, while the two processes are causally unrelated. A causal relation is difficult to demonstrate even in the case of the Sun, although the evidence for electron beam heating in many solar flares is compelling. A causal relation between particle acceleration and coronal heating is however supported if the energy in the non-thermal electrons is sufficient to heat the observed plasma.

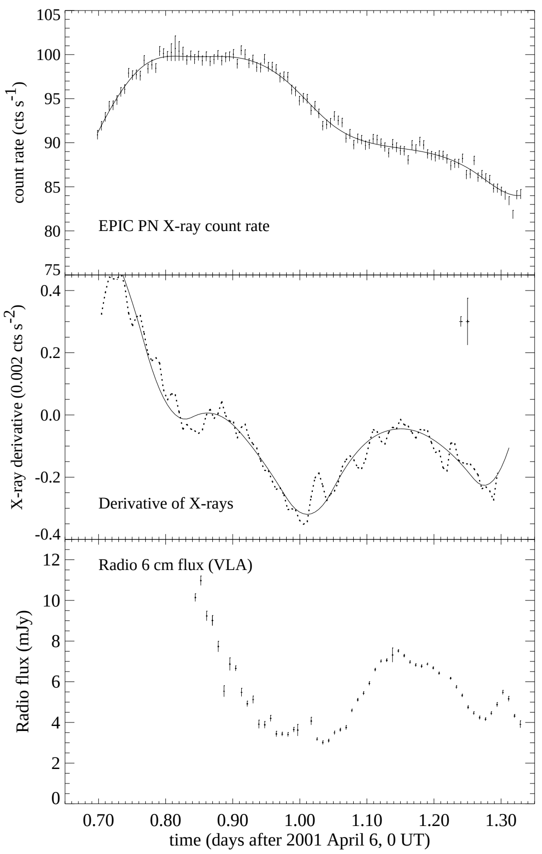

Figure 1. Light curves of σ Gem. Top: XMM-Newton EPIC PN light curve, binned to 500 s and corrected for dead time. The solid curve is obtained from boxcar smoothing. Middle: The time derivative of the smoothed X-ray light curve. The larger error bar in the upper righthand corner illustrates the absolute uncertainty for any single derivative. The smaller error bar indicates the relative scatter between nearest neighbors and is smaller due to correlations introduced by smoothing. Superimposed is a curve made by estimating the derivative using a Gaussian-filtered EPIC lightcurve, which yields a smoother function. Bottom: The VLA 6 cm light curve, binned to 690 s (scan length).

By estimating the gyrosynchrotron radio flux and assuming reasonable magnetic field strengths and electron distributions, we infer the total kinetic energy in the electrons at any given time. By integrating the energy across the flare, we can compare the total injected energy with the total X-ray losses. We assume the electrons are distributed in energy in a power law with a lower cutoff energy, E_0. In the case of optically thin plasma, the gyrosynchrotron flux is related to the total number of electrons in the emitting volume. The transition from optically thin (high) frequencies to optically thick (low) frequencies occurs at 10-20GHz, but may be lower. The spectral index at optically thick frequencies is typically $+1$. By comparing the gyrosynchrotron emissivity with the $+1$ optically thick spectral slope we can estimate that the unabsorbed flux at 5 GHz is 1 to 10 times as high as measured. Our estimate of the gyrosynchrotron emissivity naturally includes assumptions about the magnetic field strength. We set the lifetime of the electrons to 1500s, by comparison with the fastest observed decay times in the radio lightcurve. This assumption is borne out by the fact that the radio peaks lead the X-ray derivative by only a small amount, indicating rapid decay for high-energy electrons.

We can then estimate the energy injection rate, and hence the total energy, from the radio lightcurve, and compare these to the X-ray flare energy. The estimate from the radio data is that the total injected energy is of order 10^{33}-10^{36} erg. This compares with 4.5×10^{34} erg from the X-rays. Figure 2 shows contours of kinetic energies in accelerated electrons, as a function of magnetic field strength and the index of the electron power law δ.

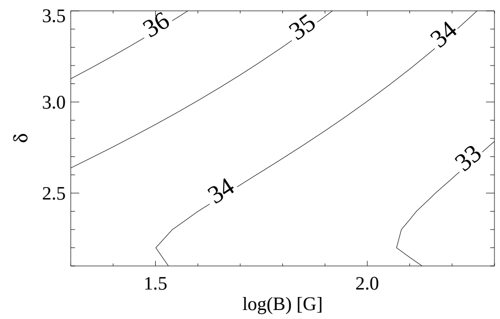

Figure 2. Estimated kinetic energies E in accelerated electrons, integrated over the complete radio flare, as a function of the magnetic field strength and the index δ. Contours are labeled with logE.

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