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DC ELECTRIC FIELDS IN SOLAR FLARES: THEORY MEETS OBSERVATION

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Abstract

The DC electric field model is briefly summarized, and some of its predictions relevant to the Yohkoh satellite and the Nobeyama Radioheliograph are discussed. These include spatial, spectral, and temporal characteristics of hard X-rays and the spatial distribution of microwave emission at 17 GHz.

1. Introduction

The DC electric field model of solar flares has received much attention in recent years (Holman 1985; Tsuneta 1985; Moghaddam-Taaheri and Goertz 1990; Benka and Holman 1992, 1994; Holman and Benka 1992; Dennis et.al. 1994; Zarro et.al. 1994). Consistent with the observation that flares occur in regions of high magnetic shear, the model assumes the presence of one or more discrete current channels. The channels may be either sheets or filaments. They are constrained in one dimension, perpendicular to the ambient magnetic field, by Ampere's law. Since the corona has a low but nonzero resistivity, the presence of currents means that a macroscopic electric field must be present. The current channels are hotter than the plasma in which they are embedded, and dissipate energy at a rate $Q = \vec{J} \cdot \vec{E}$ ergs $\mathrm{cm}^{-3}\ \mathrm{s}^{-1}$. The heated plasma emits thermal X-rays which, if the temperature is high enough, extend to the hard X-ray (HXR) regime. At the same time, electrons in the current channels having momentum exceeding a critical momentum (p_{cr}) are freely accelerated by the electric field, unhindered by collisions. These runaway electrons are then either stopped by the denser chromosphere where they emit thick-target HXRs or escape to interplanetary space on open field lines. The current channels are of finite extent in all three dimensions. This means that: (i) there is a maximum energy gain for a runaway electron determined by the length of the channel and the strength of the field; (ii) it is possible for the runaways to escape the accelerating field in the constrained transverse direction, which can be on the order of 1 m; and (iii) for classical resistivity, the flux of runaways in each channel is limited, requiring multiple oppositely-directed channels to account for the observed HXR emission. In the prsence of a sufficiently strong magnetic field, the Joule heated plasma will also emit thermal gyrosynchrotron radiation. However, nonthermal gyrosynchrotron emission requires runaways with high perpendicular momenta. Such electrons can be either scattered out of the current channels in the transverse direction or mirrored in a converging magnetic field.

The model therefore has both thermal and nonthermal aspects to it, and has many observable consequences. Further details of the model can be found in Holman (1985) and Benka and Holman (1994). The most important parameter for assessing the relative importance of thermal and nonthermal processes is $\epsilon \equiv E/E_D$ where E is the electric field strength and $E_D = p_{th}\nu_{th}/(e\gamma_{th})$ is a characteristic quantity of the plasma called the Dreicer field which depends on temperature and density. Here, e is electron charge, ν_{th} is the thermal collision frequency, and $p_{th} = \gamma_{th} m v_{th}$ with $v_{th} = (kT/m)^{1/2}$. Our use of ν_{th} shows that we assume classical resistivity, although an anomalous collision frequency is easily incorporated. A field of strength $\epsilon = 1.0$ would subject the entire thermal distribution to runaway acceleration. The model itself breaks down for these very strong fields. For interpreting the data, we have found that generally $\epsilon < 0.25$. For the higher values in this range (say $\epsilon > 0.1$), the energy flux in the accelerated electrons may exceed the already substantial energy input due to Joule heating. This is because as ϵ increases, p_{cr} is lowered toward p_{th} and more electrons are in the runaway regime. As ϵ decreases, both acceleration and heating are of comparable importance and their coexistence can have profound observational consequences. Finally, for very small values of ϵ (below say 0.04), thermal processes will dominate unless supressed.

Some of the soft X-ray implications are addressed in other papers in these proceedings (Dennis et.al.; Zarro et.al.) and I will focus on hard X-rays and microwaves.

2. Hard X-Rays

Benka and Holman (1994) applied this model in detail to the flare of 27 June 1980, observed with very high HXR spectral resolution (Lin et al 1981). Among their findings, they confirmed the hypothesis of Lin and Schwartz (1987) that the emission consists of two components, one whose time profile rises and falls gradually, and the other a series of short duration spikes superimposed on the gradual component. Benka and Holman showed that the gradual component of hard X-rays was well modeled by using both thermal and nonthermal bremsstrahlung, coupled by the common temperature of the current channels (in this simplified version, the plasma is isothermal and multiple channels are assumed to have the same average properties such as temperature, density, electric field strength, and size). The thermal emission is the main contributor at the lower photon energies ($\varepsilon <$ 20–40 keV) and falls off exponentially at higher energies. The remaining hard X-rays are nonthermal thick-target bremsstrahlung produced by the runaway electrons. The spectrum of this nonthermal emission is very hard, gradually softening at high photon energies due to the finite potential drop along the acceleration region. This softening at high energies will be observable with high spectral resolution unless some other (e.g. stochastic) acceleration mechanism takes over.

This model can thus make a prediction about the spatial distribution of the HXRs with respect to energy and spectrum. If the current channels are aligned with closed magnetic structures in the corona, then the heated plasma is also in the corona, distributed throughout the volume occupied by the currents. This will result in an extended coronal source of X-rays. This extended source, being thermal, will only be apparent at lower photon energies and will have a soft spectrum. Meanwhile, the runaway electrons are accelerated along the currents, eventually being injected into the thick-target chromosphere. This will result in one or more compact sources of nonthermal hard X-rays, located at the loop footpoints, having a hard spectrum which will likely extend to higher energies than the coronal source.

We expect many events in which both thermal and nonthermal HXRs are so observed, but they need not both be present. For instance, only the thermal emission will be observable if (i) the flux of runaways is too small to generate detectable thick-target HXRs, as would be the case for small values of ϵ, and (ii) the thermal emission measure is large enough to be observed. Only nonthermal footpoint emission would be observed if ϵ is high enough and either (i) the temperature in the current channels is too low for significant thermal HXRs or (ii) the heat transport out of the current channels is too slow to build up a high enough emission measure. This could be the case for very short impulsive events.

Another finding of Benka and Holman (1994) was that the spikes, superimposed on the gradual emission in the time profile, show a spectrum fully consistent with simple runaway accelerated thick-target emission. Isolating this emission requires subtracting out the simultaneous gradual component emission, discussed above. The resultant spike spectra are very hard and show no (or at best very little) evidence for thermal emission, even at the lowest energies. These spectra are very well modeled with only nonthermal HXRs due to runaways.

This leads to a different prediction: during the brief spikes of HXRs, additional nonthermal footpoint emission should be observed, with no (or at most very little) coincident change in the coronal thermal emission. This additional footpoint emission during spikes may be in the same location as that of the gradual component. If it is, then we would observe an increased HXR flux from the footpoints during spikes. It is also conceivable that, during the course of a flare, an instability is triggered in a neighboring magnetic structure, resulting in either a rapid transfer of runaways or a rapid generation of new current channels. This could result in the additional nonthermal HXRs appearing in a new footpoint.

There are thus three general observable consequences of the electric field model: spatial, spectral, and temporal. We expect a soft HXR spectrum in an extended coronal source, observable throughout an event that is not "too impulsive", i.e. allows thermal emission to be observed. We also expect a hard HXR spectrum in one or more footpoint sources, observable if the electric field is strong enough, i.e. ϵ is large enough. We also expect that, during spikes, additional footpoint emission is seen.

3. Microwaves

The combined thermal and nonthermal nature of the electric field model has been explored for microwaves by Benka and Holman (1992), but without incorporating the actual electric field physics, as was done for HXRs. Nevertheless, we can say with some confidence that emision at 17 GHz should be optically thin nonthermal gyrosynchrotron radiation for the majority of events. It is important to note that this emission requires the nonthermal energy of the electrons to be directed *transverse* to the magntic field, although the current channels must be *parallel* to the magnetic field for runaways to be accelerated as required by the HXRs. There are two possible ways for this emission to arise in the electric field model, scattering and mirroring.

The individual current channels, whether sheets or filaments, have been shown to be very thin (Holman 1985; Tsuneta 1985; Benka and Holman 1994). It is reasonable to expect them to be subject to various instabilities, perhaps even being disrupted and reforming continually. Such disruptions can introduce enough nonthermal electrons into the ambient plasma, with high enough perpendicular momenta, to account for the microwave emission. The generation of plasma wave turbulence in the current channels could also scatter enough particles, at a large enough angle, to suffice. If such processes as these are important for the generation of nonthermal microwaves, an extended source of this emission is expected, analogous to the coronal source of thermal HXRs discussed in the last section.

If, on the other hand, the currents are located in a converging magnetic field, it is quite possible that some of the nonthermal runaways will mirror near the footpoints. In this case, in a highly localized region, these nonthermal electrons will have *all* of their energy directed perpendicular to the magnetic field. Further, the field in this region will be significantly stronger than in the corona. Both of these circumstances are very favorable for the emission of gyrosynchrotron radiation. It was suggested from the limited data analysis done in Benka and Holman (1992) that mirroring was the likely source of this emission.

Thus the predictions for Nobeyama are that at 17 GHz the emission is nonthermal gyrosynchrotron radiation coming from either an extended, diffuse coronal source or one or more very compact footpoint sources. There is nothing in the model to exclude the coexistence of both of these sources of emission.

4. Conclusion

Are any of these predictions confirmed by observations? The answer is an unqualified "yes". Numerous papers in these proceedings (e.g. Kosugi et.al.; Masuda et.al.; Sakao et.al.) have shown HXT results consistent with the electric field model. In particular, compact double sources having hard spectra are often seen, and are associated with footpoint emission. At the same time, extended sources having soft spectra are also seen (Masuda et.al.). For disk events (e.g. Sakao et.al.) the extended source envelops both compact sources. For limb events (e.g. Kosugi et.al.) the extended thermal source is clearly seen to be coronal. Furthermore, during spikes in at least one event (Sakao et.al.) additional footpoint emission is observed. In microwaves, the spatially resolved emission is often seen to be consistent with our expectations (e.g. Enome et.al.; Nishio et.al.; Nakajima et.al.).

Much other evidence, coming from Yohkoh, also supports the notion that electric fields can provide simultaneous heating and acceleration in flares. A few examples from this symposium are discussed briefly here. Strong has suggested that the constant cross section of soft X-ray (SXR) loops is the result of currents flowing in them. Further, he suggests that some SXR "loops", connecting cusplike features, are themselves current sheets connecting reconnection regions. Moore et.al. have shown that an increased shear in photospheric magnetic fields correlates with enhanced coronal heating, consistent with stronger currents being built up. Bruner et.al. show that the plasma temperature is higher at the tops of loops than at the footpoints, and argue that direct plasma heating is required at the tops. Both Khan et.al. and Dennis et.al. show gradual evolution at the loop tops and impulsive evolution at the footpoints, consistent with the electric field model. Zarro et.al. have examined SXRs and HXRs simultaneously to deduce properties of the electric field.

It is clear that the DC electric field model for flares has great potential for providing a physical context in which to interpret observational data.

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