A CONVECTIVE MODEL FOR SOLAR AND STELLAR FLARES

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ABSTRACT. I outline a convective flare model. The basic problems of magnetic flare theories are pointed out. The magnetic flare theories as well as the convective flare theory are confronted with observations. It is suggested that a local runaway mechanism in solar and stellar cores is the ultimate cause of the flares. If this mechanism is driven by tides, it could provide an interpretation of the dependence of stellar activity cycle periods on rotation rates.

1. INTRODUCTION

The basic physical characteristics of flares in stellar atmospheres is their energetics and time behavior. Because flares can be very powerful on very short timescales, the flare theories must include mechanisms which can release very concentrated, local energies. All solar flares occur near magnetic structures. However, magnetic theories have problems with supplying enough energy for the largest stellar flares and for the large solar spotless flares (Grandpierre 1988, 1989). There exist observations of powerful stellar flares with a duration as short as 0.1 sec which means that the mechanism supplying the flare energy in the direction of its velocity has to have a dimension smaller than 100 km (Ambartsumian 1987). Consider such a rapid flare with energy $E=4\ 10^{31}$ erg and assume an Alfven velocity of $v_A=4000$ km s^{-1}. The magnetic field strength B required to supply this energy in the volume $V=L^3$ is $B=1.25\ 10^5$ gauss, as given by $E=(B^2/8\pi)\ L^3=(B^2/8\pi)\ (v_A\ t)^3$. Recent measurements of magnetic field strengths in flare stars show maximum values of 4000 gauss. We shall present the convective flare theory in relation to this fundamental problem.

2. THE CONVECTIVE FLARE MODEL

A shock wave is efficient in concentrating energy in a localized volume. Convection can cease at the local sound speed by the development of a sonic boom and the convective cell is transformed into high energy particle beams and shock waves (Grandpierre 1981). The sonic boom occur most easily in the upper subphotospheric regions because the sound speed decreases outwards in a star while the speed of a high velocity convective cell can grow in a convectively unstable region. Near the photosphere the energy surplus of the convective cell can escape from the cell because it turns out to be radiatively thin. The cells not reaching the sonic boom threshold below the photosphere will hardly be able to reach it in the higher layers either.

Let us assume for simplicity that the sonic boom sets up just at the base of the photosphere. Certainly, this is the best place for an inner explosion to show its effects in the outer atmosphere. The sonic boom implies that a large part of the energy of the convective cell is transformed into a relatively small volume of the shock front. This means that the density and energy of the particles are much larger than in the environment, so they can propagate easily outwards without significant energy losses. In reaching the chromospheric regions this high energy particle beam looses less energy the larger its energy surplus is. In propagating upwards it does not interact much with the environment. The efficiency of the bremsstrahlung radiation is only about 3 10^{-6} (Brown 1971; Spicer and Emslie 1988). Nevertheless, it still can produce some heating and turbulence, observed as chromospheric evaporation. The particles above the front of the beam are swept with the front. Heating and turbulence effects occur mainly from the relatively sharp edge of the beam.

The particle beams in propagating outwards can penetrate into the magnetic flux tubes lying above them. The convective flare theory suggests that the high velocity convective cells have a deep origin and therefore it is normal for them to pull the magnetic flux tubes with which they meet on their way. When the high energy particle beams are shot into the flux bundles, the particles are suddenly decelerated. Electrons and protons follow different paths in the magnetic field, therefore an electric field develops which acts as a very efficient decelerating agent. Bremsstrahlung radiation is produced effectively which we observe as flare light (forced bremsstrahlung). The high energy particles then propagate along the field lines to the footpoints just as in the magnetic field theories.

The energy of a convective cell E_{cc}, consists of an internal energy E_i, and the kinetic energy E_{kin}, such that

$$E_{cc} \approx E_{kin} + E_i = \frac{1}{2} m v_s^2 + C_v m \Delta T$$

at the local sound speed v_s. C_v is the specific heat coefficient at constant volume. The ratio of kinetic energy to internal energy can be extremely large at the sound speed, where

$$E_{kin} \approx \frac{5}{6}\frac{RT}{\mu}m, \quad and \quad E_i \approx \frac{3}{2}Rm\Delta T,$$

so

$$\frac{E_{kin}}{E_i} \approx \frac{T}{\Delta T}.$$

If $\Delta T \approx 2K$ and $T \approx 6000K$, then $E_{kin} \approx 3000E_i$, which means that the high velocity convection itself acts as an energy concentrator. At the sound speed the total energy transforms into the energy of the particle beams, shock waves, and heating. For simplicity we neglect here the shock waves and heating with a remark that their energies can be comparable or even larger than the energy of the particles. The sonic boom transforming the energy of the convective cell into that of particle beams has a front with a width l_f while the characteristic vertical dimension of the convective cell is l. Let us define a compression factor $C = \frac{l_f}{l}$. This means that the number of particles in the beam is $N = C\frac{m}{m_p}$, thus

$$\frac{1}{2}mv_s^2 = \frac{1}{2}Cmv_{pb}^2 \approx \frac{1}{2}Nm_pv_{pb}^2,$$

where v_{pb} is the velocity of the particle beams (protons and electrons), m is the mass of the convective cell and m_p is the mass of the proton. When shot into the magnetic flux tube, its energy transforms again into radiation, shock waves, magnetohydrodynamic waves and heating,

$$\frac{1}{2}Nm_pv_{pb}^2 = E_{rad} + E_{waves} + E_{heating} \approx E_{flare}$$

if we neglect here the released magnetic energy, which could be only an additional factor (Grandpierre 1988, 1989). The mass of the convective cell can be expressed with the (sub)photospheric density as

$$m \approx \rho(d)L^2l.$$

Here L is the characteristic horizontal dimension of the convective cell. In the case of the Sun the appropriate values are $\rho_{photosphere} \approx 4\ 10^{-7}$ g cm^{-3}; $v_s \approx 10$ km s^{-1}; $l \approx L \approx 10^4$ km, implying $v_{pb} \approx 10^3$ km s^{-1}; $C \approx 10^{-4}$; $v_{pb} \approx \left(\frac{l}{l_f}\right)^{\frac{1}{2}} v_s$, and $m \approx 4\ 10^{16}$ g; $N \approx 2.4\ 10^{40}$; $E_{particles} \approx 5$ keV; $E_{flare} \approx 2\ 10^{32}$ ergs, in good agreement with observations. We can derive also the timescales for the rising phase as

$$t_{rise} \geq \frac{l_f}{v_s} \approx 10^{-1} sec.$$

This shows the ability of the convective flare theory to give very short timescales. The rise time can be determined only by detailed calculations for the development of the sonic boom, giving the time dependent energy spectra of the particles.

The decay phase of the flare can be very rapid if the charge separation (produced by the electric field) acts the most effectively. Otherwise the particle beams can radiate until they are stopped near the footpoints of the flux tubes. So the convective flare theory is able to give the observed extremely short rise times simultaneously with the observed large energies. The convective flare theory is also able to provide giant energies by increasing the dimensions of the convective cell. The observed energies of $E = 10^{37} ergs$ for Orion flare stars require $L = l = 10^{5.6} km$.

3. THE ORIGIN OF THE HIGH ENERGY CONVECTIVE CELLS

The observed maximum upwards speed of the solar convective cells is about 1-2 kms^{-1} and has been shown to have a nearly spherical symmetry. There are observations showing that local high speed flows occur in the photosphere at flare onset (Bumba 1988; Zirin and Tanaka 1973). However, even these scarce observations are interpreted in a controversial way. Future systematic observations of the preflare phenomena are needed.

The convective flare theory assumes that two kinds of convective cells exist. The normal convective cells of the global, nearly spherically symmetric convection originates in the outer convection zone. The high speed convective cells, the so called primary convective cells, are generated in stellar cores locally as jets with an outward motion and reach the envelope of the star, sometimes producing sonic booms near the base of the photosphere.

Grandpierre (1984) showed that for the generation of the normal (or secondary) convective cells perturbations are needed in a large volume because the critical Rayleigh number is much larger than the actual one for a perturbation of a realistic size. Until the perturbations have a sufficient size, they are damped and so they cannot start a convective cell. But then what is producing the necessary perturbations?

The mechanism I propose is the local thermonuclear runaway which shoots high velocity convective cells into the outer layers. The basic assumption is that some kind of flow exists at stellar cores where there is also a local magnetic field with a certain strength. One candidate to consider would be the tidal flows. Opik (1972) pointed out that the planetary tidal flows has a velocity of 100 cm s^{-1} in the Sun. Dolginov (1985) calculated tidal velocities for binaries to be 1-1000 cm s^{-1}. If the plasma is moving into an area where a local magnetic field exists, it generates an electric field

$$\mathbf{E} = \frac{1}{c}(\mathbf{v}x\mathbf{B}).$$

For the generation of E=2 V cm^{-1} we need v=2 cm s^{-1} in a B=10^8 gauss field or v=2000 cm s^{-1} in a B=10^5 gauss field. Much smaller electric fields could produce the same result. This electric field then accelerates the charged particles to a large speed. The acceleration length is $l_a = \frac{U}{eE}$, where U is the energy of the particle after the acceleration. Using U=200 keV (much smaller also works, see later), the acceleration length is $l_a = 10^5 cm$. The mean free path at the core of solar type stars can be calculated as

$$l_{mfp} = \frac{U^2}{n\pi e^4 ln\Lambda} \approx 5.10^{-3} cm \leq l_a \approx 10^5 cm.$$

This means that the protons while accelerated are colliding frequently and therefore they heat matter locally to very high temperatures. For U=200 keV, $T \approx 3\ 10^9$ K. This temperature is an order of magnitude larger than the temperature at the peak of the He-flash in stellar cores. So a thermonuclear runaway develops locally. Its timescale is (Grandpierre 1990) $\tau_{ra} \approx 6\ 10^{-5}$ sec. This timescale is so short that the local temperature cannot be reduced by volume expansion. The dimension of the heated area grows exponentially until the critical Rayleigh number becomes smaller than the actual one. Then an explosive convection starts transporting all the surplus heat and the runaway stops.

It is interesting to note here that Wood (1972) calculated the planetary tides in the Sun and found that for centuries it runs in close correlation with the sunspot number and has a cycle of about 11.2 years. This value is derived from the tidal effects of Venus, the Earth and Jupiter (see also Wood 1975). The 180 years periodicity of the solar activity can be derived from the tidal function of the giant planets. Vogt (1983) constructed a diagram showing the dependence of the period of stellar activity cycles on their rotation rates. This diagram shows that for fast rotators (as BY Dra) there is a linear relationship in the sense that rapid rotators have long cycles. The fastest rotators are those that are quasi-synchronized. The convective flare theory offers an explanation for this in the presence of tidal effects. The faster the stellar rotation rate (which is accelerated by tidal effects), the slower is the velocity of the stellar tide. And when the tides are slower we can expect a longer activity period. For the stars which are not quasi-synchronuous this effect does not appear. This is consistent with the other part of Vogt's diagram, showing that for slow rotators the stellar activity cycles have a more or less constant period.

4. CONFRONTATION OF THE MAGNETIC AND CONVECTIVE FLARE THEORIES

Magnetic flare theories encounter several fundamental problems (Grandpierre 1989). The **energy problem** is that they are not able to release locally and rapidly large enough energies. This is most pronounced for the spotless flares in the case of the

Sun. The convective flare theory (CFT) can easily solve this problem.

All the magnetic flare theories (MFT) need high velocity inflows parallell with the surface of the Sun. It should be easily detected for the limb flares by the Doppler shift of the coronal spectrum lines, which are not observed. The CFT gives naturally a high velocity chromospheric upflow in the form of high energy particle beams, which is not so easily observable. This could work for the interpretation of the observed Balmer jumps too.

The **particle number problem** of the MFT is naturally solved with the CFT which leads to a large mass supply to the flare area from the inner regions of the stars.

The **problem of preflare upflows** of MFT arises because chromospheric evaporation produces maximum velocity before or at flare onset, and then the velocity decreases slowly. It is not possible to explain this with hypotheses assuming that the flare event is triggered from above (as in Kaastra 1985 or Martens and Kuin 1989). In MFT the continuum is always produced later and in lower layers than the soft X-ray radiation which comes from loop tops.

In solar flares observations have shown continuum to precede the soft X-ray emission by as much as 9 minutes. A large part of the flare radiation must heat the chromospheric and photospheric regions to produce continuum radiation (Machado and Linsky 1975). It is hard to imagine how the most energetic particles injected from above into the top of the loop could produce locally a maximum 9 minutes later than farher down. The chemical and isotopic composition of solar flare matter shows a clear subphotospheric origin. This fact is the basis for the plasmoid theory of Heristchi et al. (1989).

The analysis of Warwick and Wood (1959) shows that most of the primary flare sites lie low in the solar atmosphere, $h \leq 4000$ km for at least 40 per cent of the flares. The MFT work with coronal sites around 20 000 km where only 2 per cent of the flare primary sites are observed.

Poland et al. (1982) has shown by their excellent observations of a limb flare that the hot flare kernel present at flare onset is in the photosphere or very close to it. While this **problem of primary flare sites** is unsurmountable for the MFT, it is a natural result of the CFT.

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