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HELIUM(3) RICH SOLAR FLARES

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HELIUM(3) RICH SOLAR FLARES

We interpret the extreme enrichment of $^3He/^4He \geqslant 1$ in some solar flares as due to spallation and the subsequent confinement of the products in a high temperature, $kT \simeq 200$ keV, high density, $n_e \simeq 3 \times 10^{15}$ cm^{-3} plasma associated with the magnetic instability producing the flare. The pinch or filament is a current of high energy protons that creates the spallation and maintains the temperature that produces the high energy x-ray spectrum and depletes other isotopes D, Li, Be, and B as observed. Finally the high temperature plasma is a uniquely efficient spallation target that is powered by the interaction of stellar convection and self generated magnetic field.

Solar cosmic rays at relatively low energy (less than approximately 30 MeV/nucleon) coming from some solar flare events have shown that at very low energy (between 1 to 5 MeV/nucleon) ^3He is observed to have a very large value (up to 8 times the number of ^4He while deuterium and tritium are generally absent ($\leqslant 10^{-3}$ ^4He) in this energy range (Hurford et al. 1975), Anglin (1975), Serlemitsos and Balasubrahmanyan (1975).

In an earlier paper we discussed and rejected several alternate mechanisms for the production of ^3He Colgate, et al. 1977. In this paper we discuss several aspects of the solar flare model that emphasizes the evidence for the formation of current filaments as mechanisms of field dissipation, the hard x-ray spectrum and finally the extreme case of the ^3He-rich flare.

The Origin of Flare Magnetic Fields

The generally accepted view of the origin of stellar magnetic fields, Parker (1971) is that a small dipole field is amplified by a large factor by differential rotation of a laminar, i.e., non-convective core. The resulting toroidal magnetic field (actually two or more oppositely directed toroids) lies entirely within the star. The outer boundary of the toroidal field is the base of the convective zone. Convection then carries some of this toroidal flux to the stellar surface. Because convection takes place in a rotating system (the star must be rotating), the convection is partially cyclonic; i.e., a loop of flux initially in the toroidal place will be rotated - stochastically into the dipole, or orthogonal plane. The release of flux loops by resistive dissipation above the surface of the star in the dipole plane adds to the initial small dipole field and hence a generator occurs. The saturation of this generator occurs either because of a limited differential rotation stress or a limited convection stress.

The sun is a convective star and rotates. Hence on very general grounds we would expect that it would generate a magnetic field.

Regardless of the ratio of $J_\perp$ to $J_\parallel$ in the magnetic configuration below the surface, once a twisted flux loop is convected above the surface, it becomes force-free, or by definition $J_\perp \to 0$ and $J_\parallel$ maintains the configuration stress of the fields. If we choose a typical small flare energy of $W_T = 10^{29}$ ergs and typical dimensions of $R_o = 10^8$ cm, $L = 2.5 \times 10^9$, then $W_T = 2\Pi R_o{}^2 L (R_o{}^2/8\Pi)$ and $B_\theta \simeq 100$ gauss. We can also derive a current $= 5R_oB_\theta$, an inductance and inductive drop for a dissipation time of 100 seconds. These quantities are:

TABLE I

Typical Small Flare

$W_{H\alpha} \simeq 4 \times 10^{28}$ ergs	Time $= 10^2$ sec
$W_{XUV} \simeq 4 \times 10^{28}$ ergs	$B_o = 10^{2}$ gauss
$W_{everything\ else} \simeq 2 \times 10^{28}$ ergs	$I = 5 \times 10^{10}$ amperes
$W_{Total} = 10^{29}$ ergs	Inductance = 5 Henries
L = length = 2.5×10^9 cm	Voltage = 10^9 volts
$R_{pinch} = 1 \times 10^8$ cm	$E = 0.8$ volts cm^{-1}
$R_{wall} = 2.5 \times 10^8$ cm	Power = I x voltage = 10^{20} watts = 10^{27} ergs sec^{-1}

Thermal Distribution

We assume that by whatever mechanism that the joule heating is quasi-local since the "perfect" run-away fraction is small. We also assume classical thermal conductivity along the helical lines of force. Then we equate the specific joule heating source (total energy/volume x time) to the divergence of the thermal conduction flux and obtain

$$\frac{d}{dz}\left[K_o\, T_7{}^{5/2}\,\frac{dT_7}{dz}\right] = \frac{W_7}{t(L/2)\Pi R_0^2} \quad .$$

This has the solution $\quad T_7 = T_J\,[z/(L/2)]^{4/7}$ (1)

where

$$T_J = \left(\frac{W_T\ L/2}{\Pi R_0^2 t\ K_o}\right)^{2/7} .$$

Using our values from Table I, $T_J = 10^7$ degrees in good agreement with typical small flares.

Electron Density

A radiation boundary condition can be used to determine the plasma density by using a loss term for the XUV line emission in Eq. (1) rather than a heating term. The results of Tucker and Koren (1971) give $\dot{S} \simeq -\dot{S}_o\, n_e{}^2\, T_7{}^{-1/2}$ ergs cm^{-3} sec^{-1} with $\dot{S}_o = 3 \times 10^{-23}$ for $10^{-2} < T_7 < 1$. If we use this in Eq. (1), $T_7 = T_{rad}(z/z)^{1/3}$ $T_{rad} \simeq 5 \times 10^6$ degrees. If the total radiation is set equal to the total heating and we assume constant pressure, (L/2 / sound speed $\simeq$ 10 s) then:

$$n_e = n_o T_7^{-1}, \text{ and } n_o :: (W_T/\ R_o{}^2 t)^{6/7} \qquad (2)$$

and for the conditions in Table I, $n_o \simeq 10^{11}$ cm^{-3}. This gives an x-ray emission measure (n_e^2 Volume) at $T_7 = 1$ and the dimensions of Table I of 10^{48} cm^{-3}. This is typical of small flares, Peterson et al. (1973), Horan (1971).

We therefore feel confident that relatively simple measurements of energy, dimensions, and time scale lead to a plasma temperature and density distribution consistent with the fairly restrictive thermal x-ray measurements. Most importantly this analysis establishes the principal heat loss path and mechanism. It also establishes a value for the total current and electric field. If we retain this model and consider the higher energy x-ray spectra $h\nu \gtrsim 5$ keV, then the frequently observed power law spectra Kane (1973), McKenzie et al. (1973), Datlowe et al. (1974a,b), will force us to a thermal view of the origin of these photons.

High Energy X-rays

The characteristic feature of the x-ray spectrum above roughly 5 keV photon energy and extending up to 200 keV is that it can be usually and approximately described as a power law in energy $dN(h\nu)/d(h\nu) :: (h\nu)^{-\gamma}$ where $3 \leqslant \gamma \leqslant 5$, Peterson et al. (1973).

The usual interpretation of the hard x-rays is that an electron beam both carries the energy of the flare and makes the hard x-rays by bremsstrahlung on the solar surface. We feel this is unlikely because:

1. The self-magnetic energy of such a beam would be 10^{10} to 10^{12} larger than that of the flare. Colgate et al. (1977).

2. The energy spectra and total flux of photons $\geqslant 50$ keV for 37 over-the-limb flares Roy and Datlowe (1975) are similar to if not a harder spectra than face-on flares and therefore exclude thick target bremsstrahlung from the photosphere as a target for $\geqslant 50$ keV electrons.

Therefore, although we cannot give an absolute proof against the existance of an acceleration mechanism for producing equal and opposite streams, we believe the arguments against such a mechanism are strong enough to warrant an attempt to model the high energy x-ray spectra as originating from regions of higher plasma temperature and smaller emission measure as was originally proposed by Chubb et al. (1966, Chubb (1970).

Filaments

We extend the original analysis of laboratory measurements of B_z pinches. Birdsall et al. (1962) and show that the electron beam mapping of the magnetic flux surfaces are consistent with a developing singularity(ies) in the current distribution that can best be described by one, or at most several current filaments rather than a near uniform current distribution as expected and forms initially. If we extend this laboratory observation of the identical configuration of our twisted flux tube flare model where even the field strengths and densities are comparable, then we have a possible explanation of the hard x-ray origin. We suggest that the current of the flare - that maintains the twist undergoes a filamentary instability just as observed in the laboratory and predicted by the "tearing" mode instability Furth et al. (1963). Then these regions of higher current density have a higher plasma temperature exactly as calculated in Eq. (2). Here we have assumed a current dissipation mechanism that is so far not specified; only that the energy of the flare is somehow released into a plasma volume $\Pi R_0^2 L$ in a time t. Now we presume a higher temperature T_J for a smaller R, keeping L roughly constant. Since $T_J :: R^{-4/7}$, the smallest size single filament necessary to create a peak plasma temperature of $T_{max} = 200$ keV becomes $R_{max}/R_0 = (T_{max}/T_J)^{-7/4} = 3 \times 10^{-4}$ or $R_{max} \simeq 300$ meters. Note that we have retained the subscript "max" for the maximum temperature region.

If a single high temperature filament conducts laterally by the tangle flux tube model into a larger radius and correspondingly lower temperature, but at a constant pressure independent of radius or T_{max}, then $n_e = n_0 T^{-1}$, and from Eq. (1) $dVol = [R(T)]^2 dz = T^{-7/2+3/4} dT = T^{-11/4} dT$ and we obtain a spectrum:

$$N(h\nu)/d(h\nu) :: (h\nu)^{-4.25}. \tag{3}$$

This index of -4.25 falls in the middle range of the observed indices Kane (1971); Peterson (1973). Smaller values can be expected for greater confinement by the filaments as already discussed. Still larger indices can occur, because we expect a positive correlation between filament length and T_{max} meaning that the smallest diameter filaments will tend to be shorter and cooler than the above assumption. This effect will make the x-ray spectrum still steeper (a more negative index) so that we see a natural way in which a range of power law spectral indices from $2.5 \leqslant \gamma \leqslant 8$ can occur as analyzed by Peterson (1973) and Kane (1971).

Current Carriers

Finally we note that the flux of protons necessary to give the γ rays for the August 4, 1972, flare Ramaty et al. (1974); Chupp et al. (1973) of 10^{33} protons $E \geqslant 30$ MeV is just that flux if extrapolated back to 4 MeV such that all the flare current $I \simeq 7 \times 10^{11}$ amperes for 10^3 seconds must be carried by run-away protons presumedly accelerated by the inductive electric field. We therefore are led to believe that an instability (ion sound waves) immobilizes the electrons and all the current is carried by ions.

^{3}He-Rich Flares

We presume that for some reason these flares form a single quasi-stable filament that confines the current and plasma for a time $\simeq 10$ seconds. With this assumption two conditions are partially relaxed:

1. The heating rate can be smaller since presumedly it is based upon instabilities.

2. The stable confinement means that the density can be larger up to values of Eq. (2).

A ^{3}He-rich flare $^3He/^4He = 1.5$ is described by Seremitsos and Balasubrahmanyan (1975), during which roughly 5×10^{28} ^{3}He were emitted at the sun. We expect that the protons were accelerated as run-aways so that only the ^{3}He and ^{4}He must be confined by the filament. Then $n_e Vol = 10^{29}$. The hard x-ray spectral index was singularly large $\gamma \simeq -2.5$ to -3 for this flare and at $h\nu \geqslant 100$ keV, $kT_e \simeq 200$ keV $\simeq n_e^2 Vol \simeq 3$ to 6×10^{44} Van Hollebecke (1977). This extrapolates to $n_e^2 Vol \simeq 3 \times 10^{47}$ to 10^{48} at $T = 10^7$ degrees in agreement with the thermal x-ray model. Then $n_e = 3$ to 6×10^{15} cm^{-3} in a filament of $R_f \simeq 1$ meter diameter. If we take the hard x-ray burst time $t \simeq 10$ seconds, then the thermonuclear reactions will deplete the spallation product D by the necessary 10 to 100 fold as well as the light nucleii spallation products of C,O ($n_i \sigma v_i t \simeq 3 \times 10^{25} \sigma$). It should be noted that all the forward directed spallation products will continue to run-away in the electric field, $E_{\parallel}$ and be lost in the photosphere.

The proton flux at an energy of $\simeq 10^8$ eV (the potential drop along the filament) is just large enough, 4×10^{30}, to give $N_p L\sigma_{spallation} = 1$ to 2×10^{29} ^{3}He if the original ^{4}He density $= n_o/12$. In other words the extreme filament plasma conditions that satisfy the x-ray emission measure and ^{3}He confinement turns out to be just the right "hot dense" target such that with all the current carried by run-away protons that ^{3}He is just made by spallation of the original ^{4}He. If one did not have such an extremely hot (200 keV) dense (3×10^{15}) target one could not make the ^{3}He with 6×10^{10} amperes of 10^8 eV protons in 10 seconds. If the current of protons were larger, the self magnetic field would be too large. We therefore feel that the simple stable filament is a unique explanation of the peculiar circumstances required to create and process the spallation products from ^{3}He-rich flares. We do not know why such a current filament should be stable.

EXPERIMENTS

One obvious test of the filamentation and thermal models of solar flare x-rays is to measure the time necessary to reach a given ionization state that is accessible only by either a high temperature plasma $T_7 \geqslant 10$, or by the high energy electron beam flux of the nonthermal model. The two likely states are fully stripped iron, χ_{io}, the ionization potential, $\simeq$ 8 keV, and the three electron configurations if iron $\chi_{i3} \simeq 2.0$ keV. The three electron configuration is of interest because of the high binding energy and low energy resonance transition. Since χ_{i3} occurs just where $T_7 = 2$, it cannot be used effectively to discriminate between thermal and nonthermal models. The time dependence of the Lyman α radiation from Fe ($\simeq$ 6 keV) on the other hand will require $T_7 \simeq 10$ for rapid stripping. Post, 1961 has estimated the ionization rates for thermal, transparent plasma, and obtains a rate $\eta_e \sigma_i u_i = 1.5 \times 10^{-12}$ n_e. If we choose $n_o = 2 \times 10^{12}$, to 2×10^{13} and $n_e = n_o T_7^{-1}$, then the time constant for stripping becomes 3 to 0.3 seconds at $T_7 = 10$. The higher density and shorter time would correspond to the flatter x-ray spectra $\gamma \simeq -3.25$ compared to -4.25 for the lower density case. The nonthermal beam models on the other hand would be considerably lower in density; for example at $\phi_e = 10^{36}$ sec^{-1}, $R_o = 10^8$ cm, at 10 keV, $n_e = 6 \times 10^9$ cm^{-3} and the stripping rate would be several orders of magnitude slower.

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