WHAT \{ STELLAR \} RADIO OBSERVATIONS TEACH US ABOUT THE \{ SUN \}
\{ STARS \}

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ABSTRACT

Stellar analogs of solar microwave emissions are but one aspect of the solar stellar connection (SSC). In this paper I will summarize these observations and show how application of the SSC allows us to obtain fundamental insights into two important aspects of solar and stellar activity—flares and activity cycles. In the former case I note that while the sun and stars exhibit highly circularly polarized quasi-periodic microwave pulsations during flares, the stellar pulsations have much longer periods inconsistent with the usual explanation of MHD oscillations. As an alternative, I propose that interacting loops not only provide energetic particles required to produce the observed emission but that they interact quasi-periodically in a
loop with resonance time scales. In the latter case, I show that the adoption of a solar-like magnetic field geometry for other stars allows for a simple explanation of their radio polarization properties. Thus, long-term radio polarization observations should be the best way to observe stellar activity cycles.

INTRODUCTION

In the last six years a new generation of telescopes, the VLA, IUE, and Einstein, have made sensitive observations of late-type stars, many of them simultaneously. Careful analyses of these data have shown that there are many similarities between the physical conditions and processes on these solar-like stars and those on the Sun. In particular, the strong evidence for magnetic-related activity such as starspots, chromospheres, transition regions, coronae, and especially flares, has allowed us to make the "Solar-Stellar Connection (SSC)."

If one takes the SSC literally, i.e., that the underlying processes of solar and stellar activity are the same, then the differences from star to star in a particular aspect of activity can be explained in terms of the differences of the fundamental property(ies) on which that aspect depends. In this way, differences in stellar activity can serve as powerful tests of models proposed to explain that activity. For example, differences in the level of activity, observed as differences in spot or plage areas, coronal volumes, or flare frequency, are cited as evidence for a "Rotation-Activity Relation" in which rapid rotation drives the stellar dynamos
responsible for magnetic field generation (cf. Walter and Boyer 1981).

In this paper we use the SSC to investigate two of the more subtle differences in solar and stellar radio emission. In the first, we suggest that the differences in the periods of flare pulsations between the Sun and some active stars provide a clue to the triggering mechanism for flares. In the second case, we show that by assuming a solar analog of magnetic-field structure exists on other active stars we can explain several observed "curiosities" in their radio polarizations.

QUASI-PERIODIC PARTICLE INJECTION IN INTERACTING LOOPS

The flare-associated microwave emission from the Sun and active stars can be divided into two types. The first is characterized by a broad-band continuum, mild circular polarizations (CP), and (comparatively) slow variations. The second type is narrow-banded, highly-CP, and rapidly variable. It is virtually certain that the former is gyrosynchrotron radiation. The emission mechanism for the latter is unknown; however, the most satisfying "working hypothesis" is that it is due to an electron-cyclotron (EC) maser (Melrose and Dulk 1982). Occasionally on the Sun, but more often on other stars, this "EC-maser" is characterized by quasi-periodic pulsations. The pulsation timescales range from a few seconds (in the Sun) to several minutes (in RS CVn binaries).

a) Previous models of radio-flare pulsations

The usual explanation for flare pulsations on the Sun is based on fast magneto-acoustic oscilla-
tions (cf. Roberts et al. 1983). In this type of model, "sausage-type" waves form in a flaring loop producing particle traps (PT) of short wavelength. Enhanced radio emission would arise at the nodes due to the concentration of field and particles. While this type of model may be able to explain certain low-frequency solar oscillations which arise high in the corona, there are a number of reasons to suspect it cannot explain the type of microwave phenomena described earlier:

1) The observed emission is inherently narrow-banded, not broadbanded as the PT model would suggest.

2) Radio pulses are often correlated with X-ray/γ-ray pulses. The PT model predicts an anticorrelation.

3) Because there is no precipitation in upper traps (only mirroring), the PT model cannot produce the pitch-angle anisotropy required for the EC-maser.

4) It would be virtually impossible for fast particles to get into the Chromosphere/Transition Region (Ch/TR) unless the flare site was in the Ch/TR to begin with. This seems at odds with the present picture of flares being initiated high in the loops.

5) The PT models have been proposed to explain oscillations of timescale 0.3 sec. It seems impossible to extend this model to explain the much longer oscillations seen in other stars since the oscillation timescales are \(t = (\text{Alfven velocity})^{-1}\) and \(v_A\) is about the same in all stars. (The 0.3 sec oscillations could be explained within the framework of the model proposed below as particle bounce times within a flaring loop).

b) A "bouncing loop" model for reconnection

Let us consider instead a model for flare pulsations based on quasi-periodic reconnection in large
solar or stellar loops. Such a model would seem more natural in that

1) each pulse would be associated with a new injection of fast particles (which would be removed in a few bounce times by precipitation),

2) both electrons and protons would be accelerated simultaneously, satisfying the observed hard X-ray/γ-ray correlation with radio pulses, and

3) the flares would occur in regions of emerging flux.

We picture a sequence of interactions as shown in Figure 1. An emerging (young) loop presses into an existing (old) loop initiating reconnection. We presume that the resulting fast particles fill both loops equally and, through interaction with the ambient loop gas, heat the loops. What will be the response of a loop to having a fraction of its B-field annihilated and then being heated? It will expand and lengthen, the amount depending on the plasma β. However, it is virtually certain that β will be greater in the upper loop than in the lower one and therefore the mechanical response of that loop will be greater. The reconnection process should be broken off. The heated loops should expand on an Alfvén timescale (though not implicitly at an Alfvén velocity). Later cooling, principally by conduction, should cause both loops to contract and, in effect, reassemble their pre-flare configuration. Reconnection could occur again-and-again on this loop-resonance timescale provided no substantial reconfiguration of the field takes place. Observationally, 5 to 15 pulses seem typical of solar or stellar flares when oscillations are observed.

The (justifiable) assumption that the EC-maser is the radio emission mechanism allows us to esti-
QUASI-PERIODIC RECONNECTION IN BOUNCING LOOPS

(1) Emerging Loop Presses into Pre-existing (Old) Loop.

(2) Reconnection - Loop Heating and Particle Acceleration.

(3) Loops Expand on $\tau_0$, Old Loop Lengthens More! Reconnection Ceases.

(4) Loops Contract on $\tau_{\text{Cooling}}$, Try to Assume Pre-flare Configuration.

(5) Reconnection - Go to Step 3.

$\tau_{\text{Pulses}} = \tau_{\text{Exp}} + \tau_{\text{Contr}}$
mate some of the important physical parameters of the loop. First, we know that the EC-maser operates at the second harmonic of the gyrofrequency. Therefore

\[ \nu = 0.12 \nu_0 \, \text{MHz} \]  

(1)

where \( \nu_0 \) is the observing frequency in MHz. In general, we don't know the height at which the emission occurs, especially in the case of other stars. Presumably, our determined value for \( B \) is appropriate to some fraction (say 0.2) of the semi-length of the loop above its footpoint.

Dulk and Melrose (1983) have noted that the EC-maser only works in the range \( 3 \nu_p < \nu \), where \( \nu_p \) is the local plasma frequency. Choosing \( \nu_p = 6 \nu_p \), the frequency at which the maser operates most efficiently, we can then estimate the local particle density

\[ n_e \approx 10^{12} \]  

(2)

If we know or can estimate the temperature \( T \) of the loop and its height \( h \) (or length, assuming a semi-circular loop geometry) we can estimate the important timescales for expansion (from Alfvén and contraction

\[ \tau_A = 1.5 \times 10^{-11} n_e^{-1/2} h^{-1/2} \]  

(3)

\[ \tau_{\text{cond}} = 10^{-9} n_e^{-1/2} T^{5/2} \]  

\[ \tau_{\text{rad}} = 6.65 \times 10^{-10} n_e^{-1/2} T^{-5/2} \]  

If \( \tau_A < \tau \), then the maser cooling is insufficient to account for the maser cooling. Following Haisch (1983), the timescales are
The loop-resonance or pulsation timescale will be
\[
\tau_{\text{pulse}} = \tau_{\text{exp}} + \frac{\tau_{\text{conv}}}{\tau_{\text{conc}}} + \frac{\tau_{\text{cond}}}{\tau_{\text{rad}}} 
\]
(4)

c) Comparison with observations

To test this "bouncing loop" model for quasi-periodic particle injection, let us examine three cases where flare pulsations have been observed. As shown in Figure 2A, pulsations were seen over a wide energy range during the 7 June 1981 flare with a characteristic period of nine seconds (Nakajima et al. 1983). From equations (1) and (2) we find \( B = 2000 \) G and \( n_e = 4 \times 10^{10} \) cm\(^{-3} \). The upper limit to the size of the Hinotori X-ray region can be used to estimate the height; \( h \approx 3 \times 10^8 \) cm. The temperature \( T \) is assumed to be \( 10^7 \) K. Evaluating equations equations (3) and (4), we find \( \tau_{\text{pulse}} \approx 12 \) sec, in good agreement with the observed period.

In Figure 2B, we show an outburst in the dMe star L726-8A (UV Ceti's companion) where quasi-periodic pulses with a timescale \( -56 \) sec were observed (Gary et al. 1982). For this event \( B = 600 \) G and \( n_e = 3.6 \times 10^9 \) cm\(^{-3} \). We estimate the height of the loop on the basis of the probable observation of rotational modulation of the emission from dMe stars (cf. Linsky and Gary 1983; Gibson and Cox 1984); \( h = 0.3 \) R\(_s\). In this case, \( h = 7 \times 10^9 \) cm. The temperature is based on typical flares seen by Einstein (cf. Haisch 1983); \( T = 3 \times 10^7 \) K. On this basis, \( \tau_{\text{pulse}} = 46 \) sec, again in reasonable agreement with the observations.

Lastly, the remarkable 330 sec oscillations seen in HR 1099 during its large outburst of Jan-Feb 1978 (see Fig. 2C; Brown and Crane 1978) yield the
following source data: $B = 340 \text{ G}$ and $n_e = 1.2 \times 10^9 \text{ cm}^{-3}$. We use a typical flare temperature $T \sim 5 \times 10^7 \text{ K}$, based on Einstein SSS observations (Swank et al. 1981), and a height $h \sim 7.5 \times 10^{10} \text{ cm} = 0.5 \text{ R}_\odot$, based on VLBI observations (Cohen et al. 1983). The characteristic timescale $\tau_{\text{pulse}} \sim 283 \text{ sec.}$

On the whole, the agreement between the predicted timescales of the "interacting loop" model and observed pulsational timescales is good.

A PRECEDING/FOLLOWING-SPOT MAGNETIC FIELD GEOMETRY FOR ACTIVE STARS

If one examines the "handedness" of CP of active stars, one finds the following trends:

1) Those stars that exhibit substantial CP in their incoherent emission tend to be seen more pole-on, whereas those that are substantially unpolarized are seen equator-on. Equator-on stars include the eclipsing binaries Algol, AR Lac, RT Lac, and YY Gem. Pole-on stars include the spectroscopic binaries UX Ari, HR 1099, and 39 Cet and the single stars UV Ceti (L726-8B), L726-8A, and YZ CMi.

2) The polarized stars show no particular preference for the hand of CP in which they exhibit their activity. For example, HR 1099, UV Ceti, and L726-8A have always been observed to be right-hand circularly polarized (RCP) while UX Ari and 39 Ceti are only LCP. YZ CMi was originally observed to be LCP (cf. Fisher and Gibson 1982), but more recently most of its activity has been in RCP (Gibson 1984).

3) When both coherent and incoherent emissions are seen from a given star, the hand of polarization has been the same. The only exception I know of is YZ CMi (Gibson 1984).
effects, this asymmetry has the following consequences. The strength of the $B$-field in and above the photosphere is substantially smaller than that covered by the follow-up spot. This has been known for some time (Steinlof 1969).

It has been known for some time (Steinlof 1969) that the extractions of photospheric areas covered by the

(a) Implications for solar and stellar radio emission.
1) The source becomes optically thick at a given frequency at higher altitudes above the preceding spot than it does above the following spot since the principal absorption mechanism is gyroresonance absorption.

2) The effective size (cross-sectional area) of the emission region will increase with increasing wavelength. This is primarily due to the "ballooning" effect in the magnetic field once it has risen above the chromosphere. The "effective" source spectrum for the entire AR will depend on the ratio of effective areas and emissivities for the source at those wavelengths.

3) The percent polarization at a particular wavelength will depend on the ratio of the effective areas appropriate to each polarity of the B-field and their emissivities. At high frequencies the area factor should dominant and the observed hand of CP should correspond to the "following" polarity.

4) This asymmetry could even be responsible for a change in the hand of CP as a function of frequency mimicking the effect seen in uniform gyrosynchrotron source models. If true, we would no longer "know" the energy of the emitting particles, i.e., the relation \( \gamma = \frac{1}{\gamma_C} \) -- where \( \gamma \) is the relativistic Lorentz factor and \( \gamma_C \) is the fractional CP -- would not be valid, since \( \gamma_C \) would predominately be a function of the source geometry. The presumed "incoherent" emission could, in fact, arise as the sum of many little coherent sources.

5) The PFS model would also have an interesting effect on the hand of CP expected from the EC-maser model (Melrose and Dulk 1982). As fast particles stream back and forth along the loop(s) they will be "mirrored" more easily above the leading spot and
will "precipitate" more easily over the following spots. Thus, a stronger pitch angle anisotropy will be produced over the following spots favoring maserizing there. This emission would share the same hand of CP as the more intense hand of CP of the incoherent emission, in agreement with what is observed.

b) Secular changes in polarity: Implications and evidence

The PFS model would have a most intriguing effect if it is correct. The observed CP of a star would be an integrated effect of all of its AR's. Since one would expect the number of AR's in the northern magnetic hemisphere to equal the number of AR's in the southern magnetic hemisphere, one would expect to see significant CP only from those stars that are tilted with respect to our line-of-sight, e.g., tidally-locked spectroscopic binaries. This seems to be observed. Equator-on systems would not be expected to exhibit significant CP, nor do they.

If other stars undergo polarity reversals as part of their stellar cycle, as does the Sun, then it may be possible to see these reversals in the hand of CP of the microwave emission. Has such a reversal been observed? Possibly. Only the stars mentioned before have had observations reported on their CP. Algol was observed heavily from 1974-1976. UX Ari, HR 1099, and YZ CMi have been observed a number of times since 1976. AR Lac has been observed since 1978, and UV Cet since 1979. The others have been observed more recently. Only YZ CMi seems to have undergone a CP reversal; its period is about two years. For the other stars, the present statistics favor rather long cycle times (≥10-15 yr). However, much more systematic polarization and spectral monitoring of active stars must be done before evidence for polarity cycles will become convincing.
REFERENCES


DISCUSSION

SINGH: In one of your viewgraphs you mentioned that the degree of circular polarization depends on (i) viewing angle and (ii) Radiative transfer processes. A known outcome of the theory of radiative transfer is the change of circularly polarized EM waves into left-handed and right-handed polarization modes. Is this not contradictory to the observation of 100 per cent LHP and absence of RHP, as discussed by Dr. Lang in the previous paper?

GIBSON: No, it is not. Lang's observations refer to gyrosynchrotron emission where the emitting and absorbing electrons are the same. The radiative transfer affects the relative amount of emission in each hand of circular polarization when both hands are emitted in a source in which the magnetic field is "tangled". In my case the emission is coherent i.e. emitted in only one hand of CP. Radiative transfer could affect the flux but, obviously, not the per cent polarization.

LANG: 1. What role does the interaction between members of RS CVn binary pairs have in their radio emission
2. If there is any role, then how can you extrapolate radio emission from RS CVn stars to the widely spaced UV Ceti type stars?

GIBSON: 1. Proximity enforces corotation and, therefore, fast rotation. Radio emission is but one manifestation of the rotation – activity relation.

2. Not really, one would not expect the widely separated components of a dMe binary to be corotating. They are, nevertheless, rapidly rotating – because they are young and therefore, active.

EMSLIE: I have several comments regarding your "Bouncing loop" model of quasi-periodicities in flare bursts.

1. The good agreement of predicted and observed time-scale would be obtained from any MHD-type excitation: the resulting times-scale will be of order $L/V_A$, where $L$ is a characteristic length and $V_A$ the Alfvén velocity. Thus this agreement should not be taken as strong evidence for the particular geometry you suggest.

2. The energy release in the interacting loops will only cause a loop expansion if the subsequent gas pressures are high enough that $\beta \approx 1$. For the parameters you quote for the 7 June 1980 event, $\beta \approx 10^{-3}$, so it is unlikely that any expansion would occur. Even if the parameters could be changed to admit $\beta = 1$, the resulting expansion (at ~ $V_A$) should manifest itself as strong shifts in soft X-ray lines such
time-scale effects.
model, could explain some of these short
be the same from pulse to pulse in my
geometry of the interactions which would
2. Good point, I wonder whether the basic
velocity would be.

Dynamical analyses to really see what the
good deal stronger, one would have to do a
Alfven velocity. I suspect it will be a
whether the expansion would be at the
moment could be expected. I question
would be larger. In those regions some
especially in the hot stellar loops, and
would be lower in the loops. Higher up,
conditions in the accretion region which
number I quoted correspond to the
2. The numbers I quoted correspond to the
model.
ordered harmonics (e.g., the particulate trap
seem to be harder to trigger than trigger
to the fundamental mode of the loop would
suggest since oscillations in other amounts
would argue whether it is as weak as you
condition for "piddo" of the model, I
constraint on "piddo", this is not a sufficient
since when loops are triggered in the pulsar-
loops and not just small particulate traits
 Gibson: I. These timescales do suggest that entire
model can account for this.
several times. I do not see how your
509 is repeated (non-periodicity 1983, 1984, 1985, 1986, 1987). The fact that the spike
of the June 1980 event (Kitt Peak et al.
3. one of the most distinguishing features
been observed.
a-Aix. Such strong effects have never
WEBB: Referring to your diagram which showed loops in the solar corona connecting sunspots it must be pointed out that it is typically the case on the Sun that quiescent region loops and even flaring loops seen in soft X-rays and microwaves do not end in sunspots. In fact coronal emission tends to avoid sunspots. Therefore, one should be careful to note that the strong fields of sunspots are probably not associated with typical coronal emission loops.

GIBSON: My diagram does take "artistic licence". What is important is that the magnetic field structures be asymmetric which I hope you will agree is true. While coronal X-ray emission "avoids" sunspots (i.e. footpoints in this context) the brightness centroids of the radio emission tend to "move" down the legs as one goes to higher frequencies. This result occurs because X-rays are optically thin, whereas the radio emission is optically thick.