MAGNETIC FIELDS AND ACTIVITY OF THE SUN AND STARS: AN OVERVIEW

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ABSTRACT

I review recent work on the observation and theory of solar and stellar magnetic field activity and its relation to stellar activity, with particular emphasis on those aspects relevant to the problem of activity of red dwarf stars.

1. INTRODUCTION

The low-mass stars on the main sequence have long fascinated students of both stellar and galactic structure: it is in this mass range that main sequence stars may become fully convective and attain lifetimes on the main sequence comparable to the age of our galaxy; and it is these stars that provide the dominant component of the luminous mass of our galaxy and very likely constitute the dominant discrete source of the galactic component of the diffuse soft x-ray background. These various characteristics are without doubt of considerable interest in and of themselves; but it is remarkable that a number of these unique features are tied to a rather general problem of astrophysical interest: the connection between magnetic field generation in turbulently-convecting fluids and the presence of "activity".

The physical connection between "activity" on late-type (low-mass) main sequence stars and magnetic field dynamics in such stars is not well-understood. The intimate phenomenological relation between magnetic fields and the flaring activity of *UV Ceti*-type stars, and the similarily close relation between stellar magnetic fields and the optical light modulation associated with *BY Draconis* stars, have of course been long established. However, some of the most basic questions which arise cannot be easily answered: how are the magnetic fields generated in the interiors of these stars, and brought to the surface; what is the detailed relation between magnetic field emergence and stellar surface activity; how is stellar magnetic activity related to the parameters that presumably define the physical state of a star: its mass, composition, age, and rotation rate. These difficulties may be traced to at least three distinct historical problems. First, until recently, direct or indirect measurements of magnetic fields on late-type stars other than the Sun were simply not available. Second, the absence of (sufficiently-sensitive) observations which directly showed evidence for solar-like surface actvity (i.e., observations of *quiescent* emission from a solar-like outer atmosphere) allowed for the possibility that the observed phenomena were in fact rather non-solar in character; hence, the extent to which the solar analogy could be applied was not at all self-evident. Finally, both chromospheric and coronal physics, as well as MHD and dynamo theory, had not advanced sufficiently to be able to predict with any assurance the likely behavior of magnetic fields on low-mass stars, and the consequences for the structure of their outer atmospheres. This situation has now in part dramatically changed. The advent of

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the *International Ultraviolet Explorer (IUE)* and the ***Einstein Observatory***, and the application of advanced detector and spectroscopic technology at ground-based facilities in both the radio and optical domains, have now allowed study of the quiescent component of the outer atmospheres of low-mass stars and, in the course of these studies, strongly reenforced the notion that what one is observing is indeed analogous to solar surface activity (Noyes 1981; Rosner 1982). In parallel with these advances, solar astronomers have substantially enlarged our knowledge of the fine structure of the solar photosphere (cf. Tarbell 1983), as well as of the solar interior (cf. Deubner 1981); these studies provide the essential fundamental observational constraints on models of magnetic activity, as well as define the interpretive framework for stellar observations of analogous phenomena.

It is remarkable that theory now also finds itself in a period of ferment. In addition to very much increased levels of sophistication of numerical simulations (exemplified by the calculations of Gilman 1982 and Frisch 1983 and collaborators), new analytical techniques have come to the fore, most prominently the systematic application of bifurcation theory to the study of hydrodynamic and magnetohydrodynamic instabilities and dynamo problems (see N. O. Weiss in these Proceedings). The vigorous level of the discussions held at the recent IAU symposium on the subject of solar and stellar magnetic fields in Zurich (Stenflo 1983) are testimony to the excitement currently felt by both observers and theoreticians in this field; the organizers of this Colloquium have asked me to convey some of the flavor of these discussions, and to place them in the context of activity in red dwarf stars. My aim is not to provide a complete overview of magnetic activity in stars (see instead Schussler 1983 and Belvedere in this volume), but rather to call particular attention to some of the major recent results (and question which have subsequently arisen) which in my view signal a new way of looking at the problem of stellar activity.

2. ON SOME OBSERVATIONAL QUESTIONS

In much of astrophysics, successful theoretical prediction of new observational effects is a rarity; generally, the theorist is obliged to look toward observations for guidance in defining the relevant physical effects and in picking out the important (= relevant) parameter regimes to study. The student of stellar activity is in this sense hardly at an advantage since the governing physics involves the extreme nonlinearities associated with magnetohydrodynamics and plasma physics; it therefore behooves us to begin with the observations. The problem at hand is to understand the root cause of stellar surface activity; the level of difficulty of this problem is exemplified by the fact that it is by no means obvious whether the observations relevant to the construction of theories can indeed be carried through (even in principle). What then are the new observational facts that have occasioned all the excitement?

Central to the new observational perspective are the realizations, first, that stellar surface activity is common to ***all*** dwarf stars of roughly solar mass and less; and, second, that the wide range of observed stellar activity levels at any given, fixed spectral type (as manifested in, for example, stellar x-ray emission; Vaiana ***et al.*** 1981) is not simply related to the stellar properties (composition, mass, and luminosity) which largely define a star's position in the H-R diagram. Indeed, one of the major results of the ***Einstein*** surveys is that the total x-ray luminosity of late-type stars appears to be only very weakly related to the effective stellar surface temperature (and hence to the level of surface fluid turbulence). What the relevant set of stellar parameters determining stellar activity levels might involve was suggested early on by ***HEAO 1*** observations of ***RS CVn*** stars, which indicated that rotation might be a significant determinant of coronal luminosity for these binary systems (Ayres & Linsky 1980; Walter & Boywer 1981). Such a connection between rotation and ***chromospheric*** activity level was of course long known from observations of chromospheric Ca II emission from nearby solar-type dwarf stars (Wilson 1966; Skumanich 1972); but the recent work of Vaughan and collaborators (Vaughan 1983; Noyes 1983) have placed the question of the detailed correlation of chromospheric activity of late-type dwarfs with spectral type and rotation rate on a far more exacting footing. Furthermore, studies based on the *Einstein*/CfA stellar survey data have established a *coronal* luminosity-rotation correlation for isolated or effectively single late-type dwarf stars, which shows that the level of coronal emission, once a well-developed surface convection zone exists, depends little on the effective temperature of the underlying star; it seems that the x-ray luminosity data is well-described by a power law dependence on the rotation rate (with an exponent in the range 1 - 2), largely independent of spectral type (Pallavicini *et al.* 1981, 1982; Walter 1981). These studies have gained particular force since the analyses of stellar "activity" parameters have moved away from an anectodal approach; thus, substantial effort has recently been made to systematically construct stellar x-ray luminosity functions (Topka *et al.* 1982; Rosner *et al.* 1981; Rosner 1983) and to fully simulate the characteristics (including possible selection effects) of the Ca II data samples (Noyes 1983; Hartmann *et al.* 1983).

Roughly contemporaneously, the extensive modeling of solar data from *Skylab*, *OSO-8*, and the *Solar Maximum Mission (SMM)* have given us a very good idea of how stellar surface activity correlates with magnetic fields, as several papers presented in these Proceedings make clear: chromospheric and coronal activity seems to be very much tied to the emergence of magnetic flux to the stellar surface, as well as to its subsequent evolution on the surface (see, for example, Golub *et al.* 1981). Indeed, the ACRIM observations of solar bolometric luminosity fluctuations (Willson *et al.* 1981) strongly suggest that magnetic fields in the outer convection zones of stars modulate the total stellar luminosity (see also Hartmann & Rosner 1979; Spiegel & Weiss 1980). Furthermore, advances in ground-based observing techniques have led to increased understanding of the small-scale structure of solar surface magnetic fields (Tarbell 1983); and allow study of the solar interior (in particular, of the temperature stratification and rotational state of the convection zone) with the advent of "solar seismology" (cf. Deubner 1981 and references therein). In the latter case, resolution of the spectrum of the "5-minute oscillations" by ACRIM raises the possibility that similar studies applied to stars may be possible, leading to the remarkable prospect that the internal structure of convection zones on stars other than the Sun may be accessible to observational study (Hudson 1982). Thus, both solar and stellar data now give us firm observational grounds for believing that the interaction of magnetic fields with turbulent fluids is central to the problem of the chromospheric and coronal phenomenon on late-type dwarf stars; and, conversely, that one might hope to use observations of stellar surface activity to probe magnetic field dynamics in the outer convection zones of stars.

Now, there is no single, decisive, piece of observational evidence that the solar analogy is apt for stars other than the Sun; instead, at least four independent lines of reasoning converge to strongly support this analogy: first, it has now been possible to show that the classic indicators of activity on the solar surface (e.g., Ca II emission, UV transition region line emission, and x-ray emission) are observed from stars, and do correlate (cf. Pallavicini *et al.* 1982; Zwaan 1983 and references therein). Second, simultaneous ground-based and space observations of the rotational modulation of activity-related emission have shown that stellar chromospheric and coronal emission is spatially correlated with photospheric regions thought to be dominated by strong magnetic fields (analogous to the general association of sun spots with solar active regions; Kahler *et al.* 1981; Baliunas *et al.* 1983; Marcy 1983). Third, detailed modeling of stellar chromospheric, transition region, and coronal emission based on simple extensions of solar "loop" models seem to give a fairly good account of the observations (cf. articles by Dupree, Giampapa, Golub, and Linsky in these Proceedings, and by Linsky 1983 and Vaiana 1983). Fourth, the range of variability in stellar activity-related emission -- ranging from short, flare-like transients to rotational modulation and long-term, cycle-like variations -- comport with expectations based on solar observations (cf. Noyes 1983; Vaiana 1983). It therefore seems safe to conclude that, at least to first order, "activity" phenomena on late spectral-type dwarf stars may be thought of as a variant of familiar solar phenomena [although the new stellar magnetic field measurement techniques originally applied by Robinson, Worden, and Harvey 1980 yield the remarkable result that active solar-type stars can have both large magnetic field strengths (> 1 kG) ***and*** large field surface area covering factors (up to ≈ 75% of the visible disk; Marcy 1983) – these are hardly solar conditions].

Recent studies have uncovered two further facets of the data which bear on the question of stellar activity. The first effect of note is the possibility of a "gap" in total Ca II emission strength (the so-called "Vaughan-Preston gap") for any fixed (main sequence) spectral type; that is, there appears to be a range of Ca II emission levels at fixed spectral type (in the B-V range ≈ 0.45 - 1.0) in which there is a relative absence of field stars (Vaughan & Preston 1980). Since such a gap is apparently not seen in either the Li abundance or rotation data (Soderblom 1983), one might ask whether the effect is real (in which case the several contending theoretical accounts already published become relevant; see Durney, Robinson, & Mihalas 1981 and Knobloch, Rosner, & Weiss 1981), or is due to some as yet unrecognized selection effect(s). From a theoretician's perspective, one hopes that the "gap" is vindicated: a dramatic change in chromospheric activity at some fixed rotation rate would add a powerful constraint to theories of stellar magnetic activity; more observational work will be needed to establish this result.

A further interesting new result bears on the question of where dynamo action takes place in a stellar convection zone. It has been argued recently that the production of toroidal magnetic fields in the Sun must take place at large depth, basically because the emergence of magnetic fields due to magnetic buoyancy can be significantly altered only if the flux resides in a stably-stratified region (e.g., the convective overshoot region; Rosner 1980; Spiegel & Weiss 1980; Schmitt & Rosner 1982). A direct test of this idea would be to examine stars which do not have a radiatively-stratified interior: that is, the fully-convective M dwarfs. Such a study has been carried out recently by M. Giampapa (1983), with the remarkable result that main sequence M stars of very late spectral type seem to show (with considerable statistical uncertainty) an absence of Hα emission (an effect which seems to find some corroboration in the available x-ray data for very late dwarf M stars from the ***Einstein*** data; see L. Golub in this volume). This is a result well-worth of further pursuit.

3. ON SOME THEORETICAL QUESTIONS

What is the underlying physical basis for the observed correlations between stellar activity, rotation, and magnetic fields? It is probably fair to say that a complete answer currently exists only at the level of a "cartoon explanation", based on the ideas outlined by Parker (1979): a regenerative magnetic dynamo in a rotating, convecting star produces magnetic fields which inevitably rise to the stellar surface, where these magnetic fields are continually "jostled" by the turbulent convective surface motions; this "jostling" of the emerged fields presumably leads to plasma heating, and hence to a chromosphere and corona.

Can one do better than this qualitative description? Upon closer examination, the theoretical underpinnings of our current understanding of stellar activity dissolve into a myriad of subproblems, each of which is in its own right not well-understood at present: formal kinematic and dynamical dynamo theory, turbulent magnetic field diffusion, magnetic flux tube formation and dynamics, and so forth. A first-principles theory (which starts with the equations of stellar structure and Maxwell's equations, and attempts to predict, for example, coronal emission levels as a function of, say, stellar composition, mass, age, and rotation rate) thus seems well out of reach; a more realistic assessment of the immediate future of theory (at least as regards the dynamo problem) is given by N. O. Weiss in these Proceedings. In the following, I would instead like to briefly explore the current status of some of the major theoretical elements which enter into the discussion of magnetic field-dominated stellar activity.

The theoretical problems which arise in discussing the "rotation-activity" and "magnetic field-activity" connections can be conveniently grouped into two distinct categories, in each of which substantial progress has recently been made:

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(i) Dynamo theory and the "rotation-activity" connection. The problem of magnetic field generation in the solar interior has been attacked from both the point of view of full simulations and "model" (non-linear) calculations. The general status of dynamo theory is reviewed in these Proceedings by G. Belvedere (see also Schussler 1983); and the latter (non-linear "model") calculations are covered in some detail in N. O. Weiss' discussion in this volume. I will therefore not dwell further on non-linear "model" calculations, except to point out that such calculations are the best antidote to the impulse (felt by some) to extrapolate the behavior of classic linear (kinematic) dynamo theory to the non-linear domain: as can be seen from, for example, the recent calculations of Cattaneo *et al.* (1983), the solutions to the non-linear MHD equations bear little, if any, resemblence to the solutions of the linear problem.

Because the recent full magnetohydrodynamic (numerical) simulations of convection and dynamo action in spherical shells carried out by Gilman (1982, 1983) would appear to be most relevant to the specific problem of predicting surface magnetic field activity levels as a function of stellar parameters, I would like to focus on these for the moment. Among Gilman's several general conclusions, the most relevant to the present discussion is that the "α-effect" (due to non-vanishing mean helicity of motions on fairly large scales, which results in the generation of meridional magnetic fields from toroidal magnetic fields) appears to be far more vigorous than previously suspected (to the point that, in the limit of using standard values for the eddy transport coefficients, one obtains Coriolis force-dominated solutions -- an "α^2-dynamo" -- rather than the standard "$\alpha\omega$-dynamo"). As pointed out by Gilman, these results are subject to several major qualifications: first, because of limited spatial resolution (imposed by computational limitations), the formation and dynamics of "flux tubes" cannot be followed; the limited spatial grid resolution is also responsible for the inclusion of eddy transport coefficients (because the scales on which true diffusive behavior occurs cannot be modeled simultaneously with the large spatial scale dynamics; in contrast, see Frisch, Pouquet, & Meneguzzi 1983). Second, the calculations are not consistent in their treatment of compressibility; in particular, magnetic buoyancy is not accounted for. Finally, although turbulent magnetic diffusion is allowed for, the effect of helicity due to motions on small spatial scales (which enters in standard mean-field dynamo theories) is not. Are these limitations fatal to any attempt to use such simulations in understanding stellar activity? The inclusion of compressibility (as for example in the Boussinesq limit proposed by Spiegel & Weiss 1981), and the consistent application of eddy transport coefficients would appear to be straightforward extensions of Gilman's calculations. More problematical is the proposition put forward by U. Frisch that *any* simulation which invokes eddy transport coefficients cannot be rightly viewed as a full simulation; and that simulations which do not appeal to eddy diffusivities cannot be made sufficiently complex, given the forseeable state-of-the-art in large-scale computing, to realistically simulate the solar convection zone and its full dynamo properties. It is not obvious whether this argument will be vindicated; but I suspect that the results of model non-linear calculations (as exemplified by the calculations shown here by N. O. Weiss) suggest its correctness: even relatively simple non-linear systems of equations appear to have an amazingly rich repertoire of behavior, so that it would not be surprising that the full solar dynamo problem (which does not invoke eddy diffusivities) is similarly (if not far more) complex.

Now, more generally, consider the evolutionary stellar spindown problem on the main sequence: in simplest terms, what is the angular momentum loss rate as a function of stellar parameters? Note that the seemingly much simpler question of solar angular momentum loss (and its correlation with solar activity) cannot be easily answered (because present solar wind measurements are largely restricted to the ecliptic). Unfortunately, the position of the Alfven radius R_A and the mass flux at R_A are not observables for late-type dwarf stars (Hartmann 1983); nor does theory readily provide these as a function of stellar parameters (Roxburgh 1983). In fact, even the classic spin-down time scale argument is now in doubt: using the specific angular momentum dependence on mass [$\log J \sim (2/3)\log M$] obeyed by early-type stars (Kraft 1967) as an initial condition for solar-type stars, and assuming solid-body rotation, one can constrain the time scale for solar spindown; however, recent observations of global solar oscillations have cast considerable doubt on the solid-body rotation hypothesis (cf. Claverie *et al.* 1981), so that the spin-down time scale is not well-defined. It hence seems that at present, there is no proper theory which can connect stellar spin-down to the level of surface activity, and subsequently to the state of interior rotation (which presumably largely determines the workings of the dynamo processes that lead to spindown itself). That will be a tall order for the future.

(ii) Flux tube dynamics and plasma heating. The presence of inhomogeneous magnetic field structures (= flux tubes) at the solar surface seems to be an essential aspect of the inhomogeneity of the solar outer atmosphere. Two basic questions arise: how are these field structures formed (e.g., are they surface phenomena, or do they reflect a basic result of the interaction between turbulent fluids and magnetic fields); and how do they participate in the energetics of the hot outer atmosphere overlying the photosphere. Within the past few years, much work has been done on the question of the formation of thin flux tubes at the solar surface; and until very recently, these studies could be distinguished into two general categories: those calculations in which the flux tube is viewed as the endproduct of an MHD instability at the solar surface (viz., Spruit 1983), and those in which magnetic field concentration is regarded as a consequence of organized flows (i.e., granular and supergranular flows) in the solar convection zone (Galloway, Proctor, & Weiss 1977; Proctor 1983). The past year has, however, seen the suggestion of yet a third possibility: that (in the context of dynamo models in which toroidal flux generation largely takes place in the overshoot region of the convection zone -- the "shell dynamo"; Rosner 1980; Spiegel & Weiss 1980) double-diffusive instabilities lead to flux tube formation at the base of the convection zone (Acheson 1978; Schmitt & Rosner 1982; Hughes 1983; Rosner 1983). Which of these processes really occurs is not at all clear; however, very recent numerical simulations of surface convection and its non-linear interaction with ambient magnetic fields by Nordlund (1983), and their uncanny resemblence to high spatial resolution observations of solar surface magnetic fields and flows shown by Tarbell (1983), seem to suggest that flux concentration in the downflow regions of convection flows is inevitable, even if one were to start with an initially uniform field (see also Galloway *et al.* 1977).

Given the strong spatial intermittency of solar surface magnetic fields, and the spatial correlation between these magnetic fields and enhanced chromospheric and coronal activity (which extends to correlations between the photospheric field and the coronal gas pressure; Golub *et al.* 1980), it is not an unreasonable supposition that the above-mentioned magnetic flux tubes also play a crucial role in the transfer of mechanical energy from the stellar surface (photosphere) to the overlying tenuous plasma. For the theoretician, study of the possible wave modes on flux tubes (which may be involved in this energy transfer process) has proved to be fertile grounds for detailed calculations (cf. Roberts 1983; Spruit 1983). An interesting new idea is that the absorption of wave energy can largely occur in discrete frequency intervals, e.g., that standing modes are set up on flux surfaces, and that these standing waves are damped (largely by viscous forces); if, in addition, it can be shown that the resulting resonance on each flux surface has high Q (i.e., is only weakly damped, so that wave amplitudes are large, and the absorption frequency interval for that flux surface narrow), then the heating rate may be independent of the details of the dissipation process, and the bulk heating properties of coronal structures may be calculated without detailed knowledge of the local heating process (Ionson 1982). Some discussion of this "lumped circuit" approach to coronal flux tube heating in the context of solar flares by D. Spicer can be found in these Proceedings.

4. CONCLUSIONS

The above overview represents a very personal outlook on the problem of stellar activity and its relation to magnetic field dynamics in stellar convection zones. Central to the picture I've attempted to sketch is the assertion that one can meaningfully extrapolate our present-day

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knowledge of solar physics to the stellar domain (indeed, the hope is that the association between hot plasma in the outer layers of the Sun and solar surface magnetic fields goes beyond the relatively narrow confines of solar physics, and may represent a kind of generic behavior of astrophysical objects whose surfaces are turbulent; Vaiana 1981; Rosner, Golub, & Vaiana 1982); the validity of this extrapolation seems to be on fairly secure grounds at least as far as late spectral-type dwarf stars are concerned. Thus, the overall scheme is not only to take advantage of solar observations in order to provide an interpretive framework for discussing stellar observations, but also to use manifestations of activity on stars other than the Sun as an additional observational constraint for exploring the complex interaction between magnetic fields and turbulent fluids which we observe on the Sun. In fact, from the solar perspective, one might hope that the kinds of observations and modeling which will be discussed at this Colloquium will provide additional constraints on both theories of chromospheric and coronal heating and magnetic flux generation (e.g., dynamo theory) which cannot be obtained independently from solar work.

One must however temper these optimistic points-of-view with the caution that it remains unclear to what extent the rapidly-burgeoning new observational and theoretical work has begun to make more solid contact between theory and observations than has been heretofore the case. Over a quarter of a century have passed since the classic dynamo paper of E. N. Parker (1955), which in the immediately-following years had raised the (so far unrealized) hope that the solar activity cycle could be understood from first principles. We think we now know better; dynamo theory and the physics of flux tube formation are now known to be far from well-understood; and the recent new Ca II, UV, and x-ray observations have shown that the behavior of "activity" on stars is substantially more complex than hitherto suspected. It thus appears that a major task for the immediate future will be the problem of understanding how current theory and observations relate.

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DISCUSSION

Mullan: Can I ask whether there is a connection between flares and coronal heating or do you thing that those topics should be discussed separately?

Rosner: I don't think that they are intimately related. Clearly there is a relation. There is a class of solar flare which occurs in loop geometries in which the physics may be related. But to say something in detail is awfully difficult at this stage.

Kodaira: You used an illustration which showed the relation between Ca II H & K flux and rotation period. Rotation is determined by two methods, the one spectroscopic and the other photometric. Does your ordinate make an allowance for sin i in the data from the former method?

Rosner: Firstly, the illustration in question plotted X-ray luminosity against equatorial rotational velocity not Ca flux. Secondly, in the case of the spectroscopically determined data, it is v sin i which is plotted. So these points will be shifted by a factor sin i.

Kodaira: Stellar astrophysicists are accustomed to looking at plot against v sin i. Looking at this diagram it appears that the scatter is about that expected from the sin i effect. In this case I strongly suspect that the X-ray emission may be confined to the equator or at least to lower latitudes.

Rosner: Yes, that is perfectly plausible.

Gibson: (Part of question lost on tape). I don't think it is quite right to say that. Statistically stars show a rotational velocity which is about half of their equatorial velocity. This is about 0.3 in the log which is smaller than the effect in the diagram.

Rosner: The thing which we do not know is the latitudinal differential rotation rate. It is possible that this is quite large.

Kuijpers: You mentioned the Alvèn radius but did not follow it up. If one takes the angular momentum loss at the Alvèn radius does this give a proper result?

Rosner: I did not have time to address this. The answer is yes, it is reasonable. However one must be very careful when one wants to estimate angular momentum loss using mass loss and scaling the magnetic field strength. There is a coupling back since increasing the magnetic field decreases the mass loss.

Gibson: I would like to return to the question by Mullan about the connection between flaring and coronal heating. There are a number of

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telling points. Number one: when one measures the energy of the Sun's magnetic fields this is about the same as the energy needed to heat the corona. Secondly, in the case of the most active stars if one measures such parameters as densities or luminosity per unit volume then these are similar to those for small solar flares, making it look as though the stars were covered in by small solar flares. So can this question be made more strongly?

Rosner: Perhaps I did not make myself clear in answering Mullan's question. It depends on in what detail you make the comparison. If the comparison is gross, i.e. is the heating in a flare related to loops in the same way as the quiescent coronal heating is to loops then the answer is yes. If however one asks whether the precise mechanism which leads to flares is the same as that which leads to quiescent coronal heating then the answer is no.

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