THE SUN AT HIGH SPATIAL RESOLUTION: THE PHYSICS OF SMALL SPATIAL STRUCTURES IN A MAGNETIZED MEDIUM
(Invited)

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I. INTRODUCTION

It is astrophysical theory's lot to rarely predict new phenomena, and far more commonly to be called upon to provide *a posteriori* explanations for already observed phenomena. I therefore find myself in somewhat of an unusual position for a theorist in discussing what has not as yet been observed. This situation is of course familiar to the experimenter, who wants to build new instrumentation for studying phenomena at previously unexplored scales or wavelength regimes, and is in a partial quandry because theory is rarely able to fully justify this step – that, after all, is the point of serendipitous discovery. In the case at hand, I am fortunately on surer grounds: although I will be discussing phenomena which may occur on as yet unobserved spatial scales, there *are* excellent theoretical reasons for thinking that important physical phenomena can be studied on these spatial scales. But before delving into the implications of such physical processes, I would like to briefly review some of the reasons for thinking that there do exist structures in the solar outer atmosphere with spatial scales smaller than those typically accessible to present-day instrumentation.

II. SOME OBSERVATIONAL HINTS FOR "UNRESOLVED" STRUCTURES IN THE SOLAR OUTER ATMOSPHERE

The current observational evidence for substantial spatial structuring of the outer solar atmosphere on a host of scales will be extensively and ably summarized by the other speakers, but I thought it might be useful to set the stage for my more theoretically-oriented talk by noting the most basic fact about the spatial structure of the solar chromosphere and corona: there is no evidence whatever that *any* part of the atmosphere has been fully resolved, no matter what the wavelength at which observations have been carried out. A rather typical example was provided several years ago by L. Golub and N. Sheeley, who compared soft X-ray images of an X-ray bright point with EUV images of the same bright point (taken, respectively, with the S-054 X-ray telescope and the S-082 EUV instrument onboard Skylab). As Sheeley and Golub (1979) point out, the relatively small difference in nominal resolving power of these two instruments, which was not an important constraint on resolution for the normal-incidence EUV telescope), was nevertheless sufficient to show that the unresolved X-ray bright point in fact consisted of a set of very small coronal loops, duplicating in miniature the structure of active region loop arcades (Figure 1).

This suggestion, that the effective volume filling factor of hot plasma above the solar surface is much smaller than a naive interpretation of available EUV and soft X-ray images would imply, has received strong support from a succession of differential emission measure studies of the transition region. For example, in a succession of models of this layer of the atmosphere, Feldman et al. (1979) and Feldman (1983) have shown that a plane parallel description is entirely inadequate to describe its structure, a conclusion also reached by Athay (1982: see also earlier references therein). In a recent summary of these observations, Rabin and Moore (1984) presented a phenomenological model for the lower solar atmosphere in which appeal to highly localized heating (with $< 1\%$ filling factor) was made; whether or not the specific model proposed by Rabin and Moore really applies, the crucial point remains that unless appeal to highly localized energy release processes is made, it is difficult to understand the spatially *resolved* observations. Given this inconsistency with the most straightforward (i.e., plane-parallel) interpretation of the resolved observations, it behooves us to ask two questions: first (and most obvious), will higher spatial resolution observations resolve (in both senses of the word) the structure of the atmosphere; second, are there theoretical reasons for understanding why the atmosphere is structured on presently-unresolved scales, and can theory provide estimates of the likely spatial scales of this unresolved structure. In the following, I will give my personal perspective on these issues, based on recent studies of these sorts of problems I have been involved in.

III. THE THEORY OF SMALL SPATIAL SCALE STRUCTURES

The realization that important physical processes in the solar outer atmosphere *must* occur on very small spatial scales – certainly far smaller than the approximately 1 arcs (= 720 km) typically resolved by ground-based observations – goes back to the early work of Sweet (1958) and Parker (1963) on magnetic field dissipation and reconnection. The key points are, first, that we know that the solar surface magnetic fields change on time scales as short as minutes; and, second, that if one assumes the classical (Spitzer) magnetic diffusivity, then the diffusive time scale for structures of the size scale of solar active regions is of the order of years and longer. This basic difficulty first arose in the context of explaining the very short time scales associated with solar flares, but actually arises in understanding virtually any observed change in the *resolved* structure of the solar surface. The solution to this problem had to await Petschek's (1964) paper on neutral point reconnection, which showed that since the dissipative time scale varies with the square of the gradient scale length of the magnetic field, and only linearly with the inverse effective electron scattering frequency, it is essential to vastly reduce the spatial scale of magnetic field variations (even in the presence of other processes – such as scattering of electrons by electrostatic waves – which increase the effective electron collision frequency); one of Petschek's key contributions was to provide an explanation of how a sufficient reduction in spatial scales can come about. Thus, we can conclude that there *must* be processes which occur on spatial scales far below those which can be directly observed today (i.e., below roughly 1 arcs), and which have major consequences for the dynamics of *resolved* structures.

It remains to ask how small are these dissipative structures. Unfortunately, it is easy to show that their spatial scales very likely lie far beyond the resolution and sensitivity limits of planned experiments I am aware of (even if one imagines the effective electron scattering frequency to be vastly increased by, for example, scattering off ion-cyclotron waves). It is then appropriate to ask whether one expects to discover new phenomena in the spatial scale domain which we can realistically expect to reach within the next decade or so, that is, on scales of ~0.1 to 1.0 arc s (or ~ 70 to 700 km). I believe that the answer is a resounding "yes," and would like to illustrate the reasons for my optimism with two examples which arise in my own work. These examples focus on the possible geometric structure of a magnetized fluid from two rather distinct perspectives: I will first ask whether an initially uniform, magnetized, and current-carrying radiating plasma is stable; the answer turns out to depend sensitively on the precise nature of the initial state and, in particular, on what we believe might be the initial state of the gas which becomes the observed structured solar chromosphere and corona. I will then turn to a problem first explored by H. Grad and E. N. Parker, namely, whether such an initially-uniform (magnetostatic) state can in general remain magnetostatic when subjected to arbitrary perturbations; and, more specifically, what geometric and topological properties such as perturbed equilibrium might have.

(a) The formation of small-scale structure in a radiating plasma

Although it is by now generally accepted that magnetic fields are largely responsible for the formation of the Sun's corona (and perhaps its chromosphere as well), it remains puzzling exactly how the "coronal" state (i.e., a highly spatially-structured, low density but high temperature plasma) is formed. That is to say, prior to asking how or why there is small-scale (e.g., sub-arcsecond) structuring, one should be concerned with how spatial structuring into the ubiquitous coronal "loops" occurs in the first place.

The basic reason why this puzzle arises at all is simply understood by considering the expansion of the photospheric magnetic fields (which are known to be highly spatially structured on scales ranging down to the sub-arcsecond level) *above* the photosphere. It is easy to show that because the overlying atmosphere is dominated by these magnetic fields, field lines should become space-filling within a few thousand kilometers of the level of optical depth unity in the continuum. Hence, if all emerging magnetic field lines were equally loaded with hot coronal matter ("coronal democracy"), then the corona should not show any major evidence for spatial structuring in the plasma emissivity (recall that the observed coronal inhomogeneity largely reflects variations in the local plasma density, rather than in the local plasma temperature). This is of course not observed to be the case: there does not seem to be coronal democracy, some (sets of) reentrant field lines being selected out by being relatively more loaded with hot coronal plasma than others – hence the loop structuring. This selection effect, together with the observation that any given loop structure is highly variable in its emission level (e.g., highly variable in the amount of matter loaded onto that set of magnetic field lines), suggests the operation of some sort of transient or instability which leads to the "filling" of only some flux tubes. As a momentary aside, I might note that it is of substantial interest to discover the plasma conditions along those field lines which are *not* loaded with substantial amounts of hot coronal matter: to answer this question will require imaging instrumentation sensitive to emission from a broad range of plasma temperatures, as well as high spatial resolution and extremely low sensitivity to scattering (the latter is essential in order to avoid overwhelming the likely weak emission contribution from the "unloaded" field lines with the copious emission from surrounding "loaded" field lines, a problem well known at X-ray wavelengths in studies of coronal holes; cf. Maxson and Vaiana, 1977).

As an example of the kind of theory which the considerations just discussed give rise to, I will describe recent work by Ferrari et al. (1982) and collaborators which suggests that this "loop filling" process is – at least during the initial stage of magnetic field emergence from the photosphere – the result of a heating instability driven by coronal currents. We know that the pre-coronal state of coronal plasma – the initial state – must be associated with the relatively cold gas entrained in magnetic fields as the latter are brought to the stellar surface by processes such as magnetic buoyancy. The question is then what happens. This plasma, which was initially entrained by the emerging fields, cools rapidly because it is no longer radiatively heated as it enters the small optical depth regime. However, because of (for example) accumulated stresses in the emerging "flux rope," one expects current flows, and hence associated Ohmic heating. This latter heating rate is not likely to be energetically significant until the plasma density in the cool emerging "flux rope" has dropped sufficiently that the radiative losses are of order of the

Ohmic heating rate (because cross-field thermal heat transport is strongly inhibited, the cool low-density "flux rope" emerges into the hot ambient medium – the chromosphere and above – energetically relatively insulated). The question is thus whether an equilibrium between Ohmic heating and radiative losses can be maintained; and if not, what the evolution of the unstable system leads to. In this view, the hot coronal envelope of a star such as the Sun is therefore thought of as a metastable configuration evolved from a cold initial equilibrium. To study this process, one considers a model magnetized atmosphere which is hydrostatically stratified (i.e., with gravity and non-vanishing pressure gradients), is in initial radiative equilibrium, and is initially uniform in temperature; and asks how such an atmosphere responds when subjected to perturbations in local heating rate due to current flows typically induced by photospheric motions (Heyvaerts, 1974a; Jockers, 1978). In the simplest case, in which gravitational stratification is ignored, the problem reduces to solution of a straightforward dispersion relation of the form (Heyvaerts, 1974b; Ferrari et al., 1982).

$$\omega = -\,i(\gamma - 1)\,[-(\kappa_{\parallel}\,\kappa_{\parallel}^2 + \kappa_{\perp}\,\kappa_{\perp}^2)\,(T_o/p_o) + (dh/dT)|_o\,(T_o/p_o)$$
$$-\,(J_o^2/\sigma_o p_o)\,(d\log\sigma/d\log T)|_o\,(\sin^2\theta - \cos^2\theta)]\quad ,$$

where $\kappa_{\parallel}$ and $\kappa_{\perp}$ are the parallel and perpendicular thermal conductivities, respectively, h is the effective radiative loss rate, θ is the angle between k and B, and the subscript "o" denotes parameters evaluated in the equilibrium state. Instability requires that the last term in the square brackets be positive and exceed the two preceding ones in absolute value: thus, the Ohmic heating term must overwhelm the (always-) stabilizing influence of thermal heat conduction and the influence of the net (radiative) losses. This mode of interest is the Joule mode, which is essentially transverse to the magnetic field, is connected with current filamentation, and operates only in the low-frequency limit in which the plasma can rapidly diffuse across the filaments (thus avoiding a pressure build-up that would stabilize the mode).

The Joule mode instability can be interpreted physically as follows. The initial spatially-uniform current density associated with the "non-potential" magnetic fields produced by photospheric motions becomes unstable, leading to the formation of current filaments inside which Joule dissipation is enhanced. The temperature thus increases within current filaments; and the local electrical conductivity therefore increases as well. Hence, the local current density within filaments further increases and, therefore, in order to maintain energy balance with radiative losses, yet further channelization is required (thermal runaway). This process can occur in the [total current I = constant] limit because we are in the low-frequency domain in which cross-field diffusion can occur (see detailed discussion in Ferrari et al., 1982; this constant current approximation is most appropriate because of the large self-inductance of the magnetized plasma). The ultimate mechanism for stopping the channelization is not established, but as noted by Ferrari et al. (1982), the instability may saturate in the nonlinear regime because of enhanced electron scattering by plasma turbulence (which increases the diffusion rates), or because the current sheets which form become unstable to the tearing mode (see discussion of this latter point in Bodo et al., 1985). For example, if the enhanced scattering is due to ion-cyclotron turbulence, then the effective heating rate will be a strong function of the drift speed, and will act to increase current diffusion precisely in the region of current concentration.

In order to proceed beyond these calculations, one must deal with the fact that analytical dispersion relations cannot be obtained for more realistic inhomogeneous (i.e., stratified) configurations. Hence, it is necessary to resort to numerical means for solving for oscillatory perturbations as eigenfunctions of a boundary value problem (Bodo et al., 1985); one can then investigate the effects of atmospheric gradients and finite loop dimension on the scale of unstable perturbations. The equations used are the standard MHD conservation equations for mass, momentum, and energy, together with Maxwell's equations and Ohm's law. Only perturbations which are symmetric across the top of the loop turn out to be of interest, as antisymmetric perturbations can be shown to be stable. The basic features of the results obtained by Bodo et al. can be gleaned from Figure 2, in which is plotted the general dispersion relation of the Joule mode in the frequency-wave number plane. The physical parameters used in this example apply to a "classical" stellar atmosphere, without any chromosphere or corona (as may be the case for a buoyant magnetic loop, as it emerges from the solar interior at the solar surface); the results shown have greater generality than those obtained from the analytic dispersion relation written down above because they are obtained without imposing the low frequency limit. In the context of our discussion, the following features of the results are most noteworthy:

(1) There is a cut-off in the growth rate at small wavenumbers; this cut-off occurs because the plasma becomes frozen-in at these scales, so that pressure forces lead to stabilization.

(2) A second cut-off (at large wavenumbers) is also present; it is due to thermal conduction acting across sufficiently-thin filaments, which leads to suppression of local temperature contrasts, and hence to stability.

(3) For a large range of horizontal wavenumbers lying between these limits, the growth rate is roughly constant. Furthermore, this range of dominant spatial scales of the instability lies just below present limits on spatial resolution from the ground.

Thus, the thermal instability of the kind treated by Bodo et al. can actually affect loops, or portions of loops, as long as either their spatial extent or their apex densities are not too large; i.e., it will affect either the apexes of small loops in dense atmospheres, or entire small loops in rarified atmospheres. Of particular interest to the topic of this meeting is that the typical scale lengths of current filaments (= 10^3 - 10^6 cm for the cases considered) are too small to be detected by currently available direct observations, but are comparable to the dimensions of current inhomogeneities (and magnetic gradient scales) invoked in a number of in situ coronal heating models (Rosner et al., 1978; Hinata, 1980; Benford, 1983); in such models, the requirement for spatially-localized current flow is recognized, but the mechanism by which such current filamentation occurs is not detailed. The results for the thermal instability obtained by Bodo et al., and summarized here, are distinctly different from those obtained if one had started with an already existing chromosphere/transition region/corona atmospheric structure as the initial equilibrium state to be perturbed (e.g., Heyvaerts, 1974b). In this latter case, high temperature gradients along magnetic field lines are already present. Hence, a tight coupling between the low and high temperature portion of a loop is introduced by efficient thermal conduction and, unlike the case discussed here, the (cold) lower boundary can actively control the thermal evolution of the hotter overlying layers even in the linear regime (for example, see Peres et al., 1982). Because the observational evidence suggests that at least some of the coronal structures seen in soft X-rays (viz., X-ray bright points) arise as a direct consequence of the emergence of magnetic flux above the photosphere (cf. Golub et al., 1980), I believe that the assumption of a "cold" initial state for perturbed pre-coronal structures is far more appropriate than assuming an initially hot state (but note that the question of the stability properties of an already existing hot state is an important issue in its own right – and quite distinct from the problem treated here). The instability process I have briefly summarized here thus provides a natural explanation for the sudden "turn-on" of coronal activity for emerging magnetic structures, though not of their subsequent thermal evolution.

As a final note to this section, I point out that the current-driven thermal instability discussed by Bodo et al. (1985) is complementary to the arguments of E. N. Parker presented in a recent series of papers (see Parker, 1983, and references therein), who has shown that most 2-D flows on a conducting surface penetrated by magnetic field lines (such as the photosphere) inevitably lead to sheared field/plasma geometries which cannot be in magnetostatic equilibrium, and are likely to be strongly dissipative (this point is discussed further below). The shear layers which result (where in fact currents of the type required by the calculations summarized here flow) are indeed also unstable to the Joule instability discussed above; thus, further filamentation similar to that encountered in tearing may occur, but now driven by thermal effects. In general, the results of Ferrari et al. (1982) and Bodo et al. (1985) I've just summarized, together with the arguments presented by Parker (1983) and in the discussion given in the next section, suggest that magnetized plasma emerging from the solar convection zone becomes highly structured in its thermodynamic properties transverse to the magnetic field very soon after its emergence. The observations of arcsecond coronal structuring, such as those reported by Sheeley and Golub (1979) and discussed above, and the recent observations suggesting transient coronal heating within volumes having very small filling factors (Martens, Van den Oord, and Hoyng, 1985), may well be a reflection of just such structuring processes.

(b) The "ordered" versus the "chaotic" magnetized corona

A rather different perspective on the question of sub-resolution structure in the solar outer atmosphere emerges from a long-standing problem in magnetohydrodynamics: can one always construct stable magnetostatic (or magnetohydrodynamic) equilibria for specified normal components of the field on the boundaries. That is, it is unknown wnether such constrained equilibria (other than the relatively trivial force or current-free configurations) can always be devised without having some high degree of (coordinate) symmetry (see, for example, Manheimer and Lashmore-Davies, 1984, for a review of plasma equilibria and their stability properties; also Parker, 1979). This has led to the conjecture that the known difficulty of finding equilibria without coordinate symmetries is not just a computational problem, but rather that it is fundamental in the sense that the absence of equilibrium states for geometries that have no simple spatial symmetry is a fundamental property of magnetofluids (Grad, 1967; Parker, 1972, 1979).

This conjecture has recently received theoretical support from several studies. For example, Parker (1985) has shown for the magnetostatic (force-free) problem that arbitrary displacements of field line footpoints on the boundaries of a volume lead to field evolution within the volume which can be described by two independent scalar functions; but that if continued equilibrium is insisted upon as the system evolves, then one of these scalar functions is overdetermined, and that as a consequence, discontinuities (in the force-free alpha parameter) must arise. Similarly, Moffatt (1985) has recently shown that for a simple, initially current-free, magnetostatic configuration, arbitrary displacements of field lines on the boundary lead to current sheet formation. Finally, of particular relevance to the present discussion is the recent demonstration that in the absence of rigid boundaries and gravity, symmetric magnetostatic equilibria are topologically unstable (Tsinganos, 1983; Rosner and Knobloch, 1983; Tsinganos, Distler, and Rosner, 1984). That is, such equilibria have the property that (except for a special class of perturbations of zero measure) when they are subjected to arbitrary perturbations, the perturbed system is in general not guaranteed to be in magnetostatic equilibrium – pressure surfaces may no longer coincide with magnetic flux surfaces – so that the system can become dynamic.

Typically, the symmetry of the original equilibrium can be broken because singular points arise within the configuration (as discussed by Parker, 1985, and Moffatt, 1985) and, as shown by Parker (1982, 1983; see also Vainshtein and Parker, 1985), static equilibrium is not possible in the vicinity of such new singular points. Thus, the imposition of external perturbations on an equilibrium MHD structure can lead to a situation in which the system locally departs from static conditions, and local reconnection occurs (cf. reviews by Freiberg, 1982, and Manheimer and Lashmore-Davies, 1984). In the context of laboratory plasma confinement, this process is related to the destruction of magnetic surfaces and the formation of magnetic islands; in the context of heating the solar corona, Parker (1983) has extended this argument to the case for which the normal component of the magnetic field does not vanish on the surface bounding the magnetized plasma (e.g., at the photospheric footpoints of coronal magnetic structures). In this latter case, he has argued that local deviation from magnetostatics and reconnection arise in the lower solar atmosphere because of the continual deformation of coronal magnetic fields by the horizontal cellular photospheric flow field. In summary, local nonequilibrium (i.e., lack of local static equilibrium) can lead naturally to formation of localized reconnection regions and initially isolated magnetic islands throughout the loop volume.

What are some of the observable consequences of such local destabilization of coronal plasmas? Recently, E. Antonucci, K. Tsinganos, and I examined one possibility in the context of observing flare loops. Spectroscopic observations from the Solar Maximum Mission (SMM), P78-1, and Hinotori satellites have led to a number of qualitatively new observations of solar flares, perhaps the most striking of which are the data on line broadening observed during the initial stages of flares (viz., Culhane et al., 1981; Tanaka et al., 1982; Doschek et al., 1985). Thus, the onset of solar flares is characterized by large non-thermal broadening of helium-like soft X-ray resonance lines emitted by highly ionized heavy ions, such as Ca XIX and Fe XXV. This effect is usually attributed to the presence of non-thermal plasma motions (estimated turbulent velocity amplitudes derived from the presumed Doppler temperature are between 100 to 200 km sec^{-1}), and may be observed one or two minutes before the impulsive increase in hard X-ray flux (which traditionally marks the onset of flaring), and before the appearance of high-speed upflows of chromospheric material heated to coronal temperatures (chromospheric "evaporation," identified with the appearance of distinct blue wings in the X-ray lines; Antonucci et al., 1982, 1984). The excess line widths persist as long as there is observational evidence for energy release in the flare site. In the decay phase of flares, non-thermal velocities either are not observed, or are present at very low levels. The turbulence level in the plasma appears to be independent of the position of the flare on the solar disk. Although a number of interpretations of these data are possible (the most commonly-accepted of which regard the overall line profile as a superposition of various Doppler-shifted components resulting from integration along the line-of-sight of various distinct, unresolved loop structures, or parts of loop structures), we have suggested an alternative picture (Antonucci, Rosner, and Tsinganos, 1985), in which the observed line broadening is due to a superposition of Doppler-shifted line profiles arising from distinct plasma flows originating within a *single* loop structure. This hypothesis gives a good account of the data, and turns out to be a natural theoretical consequence of the lack of topological stability of coronal magnetic structures just alluded to. Consider the following key features abstracted from analysis of a large number of flares observed with the Bent Crystal Spectrometer of the SMM Soft X-ray Polychromator (SXRP; Antonucci et al., 1984; see also the extensive summary of the relevant data in Doschek et al., 1985):

(a) The non-thermal excess in the line width is symmetric about the line center of the broadened line for on-disk flares, is larger at flare onset, decreases monotonically during the impulsive phase, and occurs systematically before the onset of line blue shifts.

(b) The degree of non-thermal excess appears to be uncorrelated with the position of flares on the solar disk; i.e., there is no apparent longitude dependence of the isotropic turbulent flow parameters.

(c) When significant soft X-ray emission is detected before the hard X-ray burst, the non-thermal line broadening is observed to increase one or two minutes before the hard X-ray burst.

In summary, observations of individual flares indicate the presence of fairly isotropic flows during the *early* part of flare onset; these flows exist in addition to the systematic upward flows (which are most likely related to the initial "evaporation" of chromospheric material). The lack of any longitude dependence of both the red and blue wings of the line broadening for different flares and its symmetry suggests that the broadening is indeed isotropic (and not simply due to a superposition of Doppler-shifted components which arise within distinct, but unresolved, loops); the timing of the onset of strong line broadening calls into question its association with the evaporation process; and the fact that broadening occurs (and is largest) at the very onset of the flare argues that it is *pre-existing* (not newly-evaporated) coronal material which is responsible for the line broadening. Antonucci et al. thus argue the proposition that the observed broadening appears isotropic not because of accidental superposition of various unresolved flaring loops (and associated interior convective flows) along the line-of-sight, but because the fluid which gives rise to the observed emission is indeed isotropically turbulent in any one given loop structure (i.e., the fluid is, on the dimensions of the loop, locally isotropically turbulent).

What then is the model? The basic conjecture put forth by Antonucci, Rosner, and Tsinganos (1985) is that a loop system subjected to continual deformations applied to the photospheric footpoints will continue to evolve quasi-steadily (consistent with the field line topology imposed by the perturbation), leading to island formation and, when regions of overlapping islands have formed, to the onset of field line stochasticity, strongly enhanced local reconnection and dissipation, and enhancement of plasma transport coefficients (cf. Freiberg, 1982; in a related process, proposed in the context of a specific MHD instability, e.g., island overlap of unstable tearing modes located in distinct unstable tearing layers, has been proposed by Finn, 1975, and applied to the flare onset problem by Spicer, 1976, 1977). Antonucci et al. (1985) caution that it is essential to distinguish this succession of events from the destabilizing process previously suggested by Low (1982a,b) and others, who have argued that solar flares represent the terminal point of an evolutionary sequence of "nearby" equilibria through which a system evolves as it is subjected to external perturbations; this terminal point is reached when the sequence of equilibria ends in the sense that there are no longer any nearby equilibria to which the system could evolve. The model proposed by Antonucci et al. is distinguished from these earlier studies in that (i) it does not identify the onset of flaring with the point of termination of a sequence of nearby equilibrium states, but rather views it as the point at which a topological unstable, quasi-steadily evolving state (which need not be force-free; compare with Heyvaerts and Priest, 1983) reaches the stochastic domain; and (ii) the instability does not manifest itself in a global MHD instability, but rather in a drastic departure from statics throughout the entire volume of the system, wherever singular field line behavior as a result of island overlap, and local reconnection, occurs. These localized reconnection events are then expected to occur at the very onset of the flare – indeed, in this picture, they mark the very beginning of flare onset.

It is of course necessary to demonstrate quantitative, and not only qualitative, agreement with the observations, and Antonucci et al., indeed show that one can provide a reasonable "back-of-the-envelope" fit to the data, e.g., reconciling observed temperatures, densities, and inputed turbulent velocities with the model. In the present connection, one of the most intriguing results of this comparison with the data is that reasonable agreement with the data only follows if one assumes a rather small filling factor for the matter which actually contributes to the isotropic broadening component: the volume filled by this component must be approximately 5% of the total volume seen by the SXRP in emission. This implies (in the most naive intepretation) an upper bound on the linear dimensions of the emission volume of roughly 10^8 cm; in a physically more plausible picture, in which the emission arises within thin structures enlongated along the background ("guide") field, the dimensions of the emitting regions would be just below the arcsecond level.

The model proposed by Antonucci et al. to account for the turbulent line broadening thus has several features which make it interesting from the point of view of "sub-resolution" structure. First, it predicts rather small filling factors for the regions primarily responsible for the isotropic component of the line broadening. Second, it is likely that the reconnection sites invoked to account for the macroscopic plasma streaming will also be sites of localized particle acceleration. Observational support for this suggestion is provided by the fact that hard X-ray bursts are observed precisely during the period in which turbulent line broadening is observed. This timing coincidence is to be expected if the fast particles which give rise to the bursts have their origin in the many scattered reconnection sites invoked in the flare line broadening process itself. This would imply that particle acceleration does not occur at just a very few selected sites within a loop, but rather occurs throughout the loop volume. An especially interesting possibility is then that particles accelerated in any one such reconnection region continue to be accelerated in other reconnection regions they encounter as they traverse the loop; such multiple acceleration encounters can provide the Fermi process called for by the particle spectra deduced from the SMM hard X-ray and gamma ray observations (viz., Ramaty et al., 1985, and references therein). A third feature of this model is that it does not sharply distinguish between flare heating and the far more prevalent low-level "microflaring" (Lin et al., 1984) and other low-level transient brightening (cf. Porter, Toomre, and Gebbie, 1984) which seems to characterize the active solar corona and transition region. Indeed, as argued by Rosner and Vaiana (1978), a stochastic energy release process of this kind naturally gives rise to the observed power law dependence of the integral number of (hard X-ray) transients on peak flux (or total energy released; see also Datlowe, Elcan, and Hudson, 1974). Thus, it may be that the transient formation of dissipative structures in the solar corona is responsible for much of the overall coronal heating (cf. Parker, 1972, 1979), a process which can only be studied by looking at the Sun's outer atmosphere with instruments of high (i.e., sub-arcsecond) spatial resolution.

IV. SUMMARY

In this paper, I have attempted to provide a personal perspective on the problem of spatial structuring on scales smaller than can presently be directly and regularly observed from the ground or with current space-based instrumentation. I believe that there is abundant evidence from both observations and theory that such spatial structuring of the solar outer atmosphere is ubiquitous not only on the observed scales, but also on spatial scales down to (at least) the sub-arcsecond range. This is not to say that we can anticipate the results to be obtained from observations on these small scales: quite the opposite. What is clear instead is that many of the classic problems of coronal and chromospheric activity – involving the basic dissipative nature of magnetized plasmas – will be seen from a novel perspective at these scales, and that there are reasons for believing that dynamical processes of importance to activity on presently-resolved scales will themselves begin to be resolved on the sub-arcsecond level. Since the Sun is the only astrophysical laboratory for which there is any hope of studying these processes in any detail, this observational opportunity is an exciting prospect for any student of magnetic activity in astrophysics.

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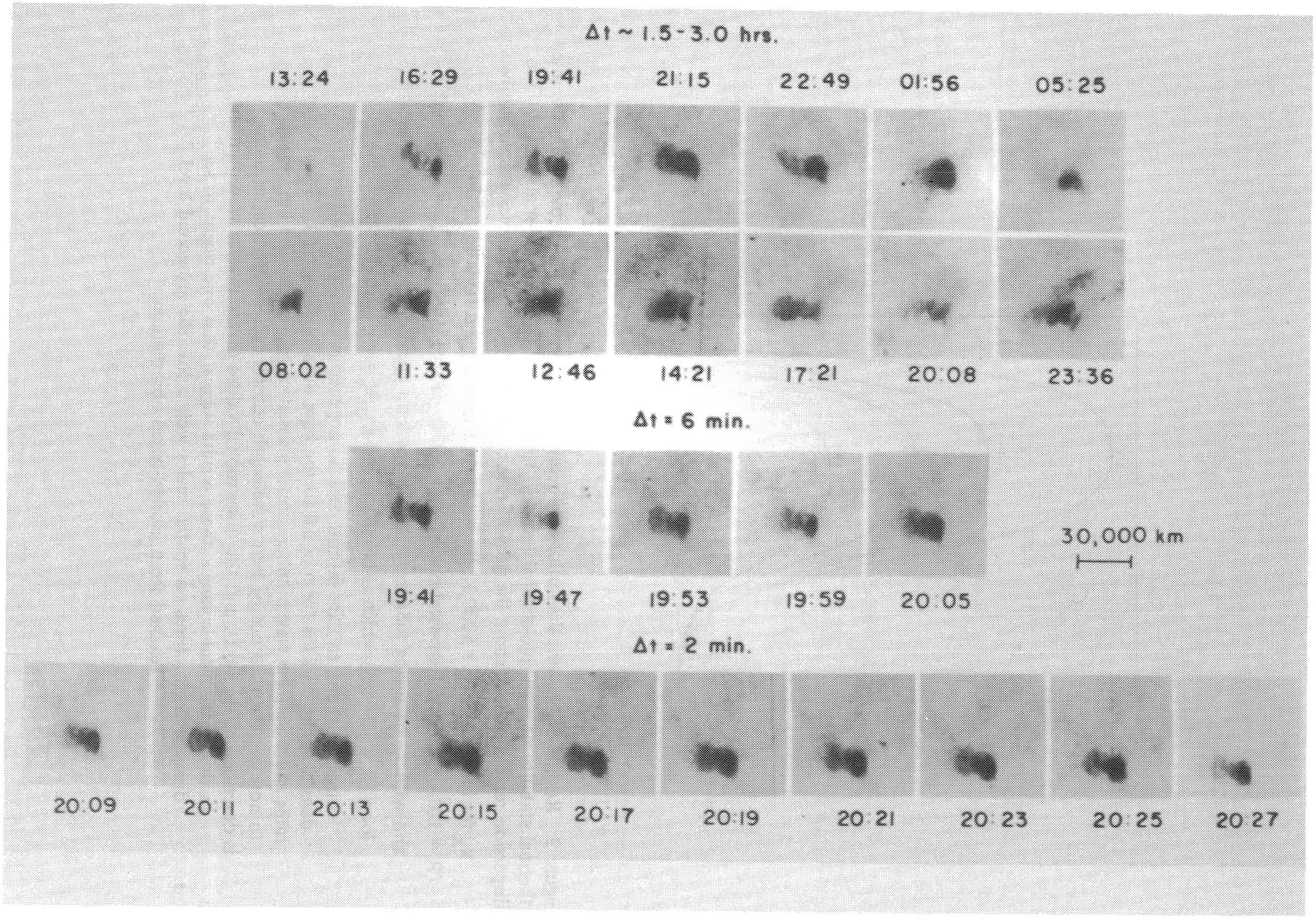

Figure 1. An example of structuring of the solar corona, seen at the very limits of spatial resolution attainable on Skylab over 10 years ago (from Sheeley and Golub, 1979). The images show a coronal bright point resolved into component "loops," much like the structure of the far larger active region complexes.

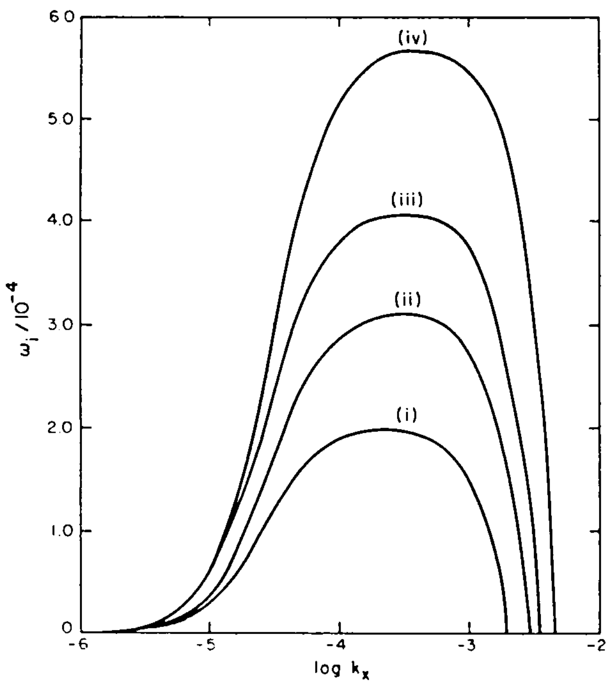

Figure 2: Results of numerical solution of the eigenvalue problem posed by solving for the thermal stability of cool, pre-coronal loops of finite extent (from Bodo et al., 1985). The dispersion relation curves show the growth rate $\omega_i(\equiv|\mathrm{Im}\ \omega|)$ versus transverse wavenumber k_x for loops with T_o = 5000 K, B_o = 100 G. Curve labeled (i) is for a finite loop ($R = 10^7$ cm) which is gravitationally stratified ($z_o/R = 1$), with $n_{apex} = 10^{12}$ cm^{-3} and with J_o balancing radiative losses at the loop apex; curve (ii) is for a finite loop ($R = 10^7$ cm) which is homogeneous ($z_o/R = \infty$), with $n = 10^{12}$ cm^{-3}; curves (iii) and (iv) are infinite and homogeneous cases with different densities; curve (iii) is for n equal to the base density of case (i). Growth rates and transverse wavenumbers are expressed in cgs units. The key results to note are the presence of two wavelength cutoffs (whose physical meaning is described in the text), and the dimensional values of the inverse wavenumber in the most unstable range: these results suggest that one ought to see dissipative structures on spatial scales well below the arcsecond level reached from ground-based observations.

SOLAR X-RAY PHYSICS