715-78

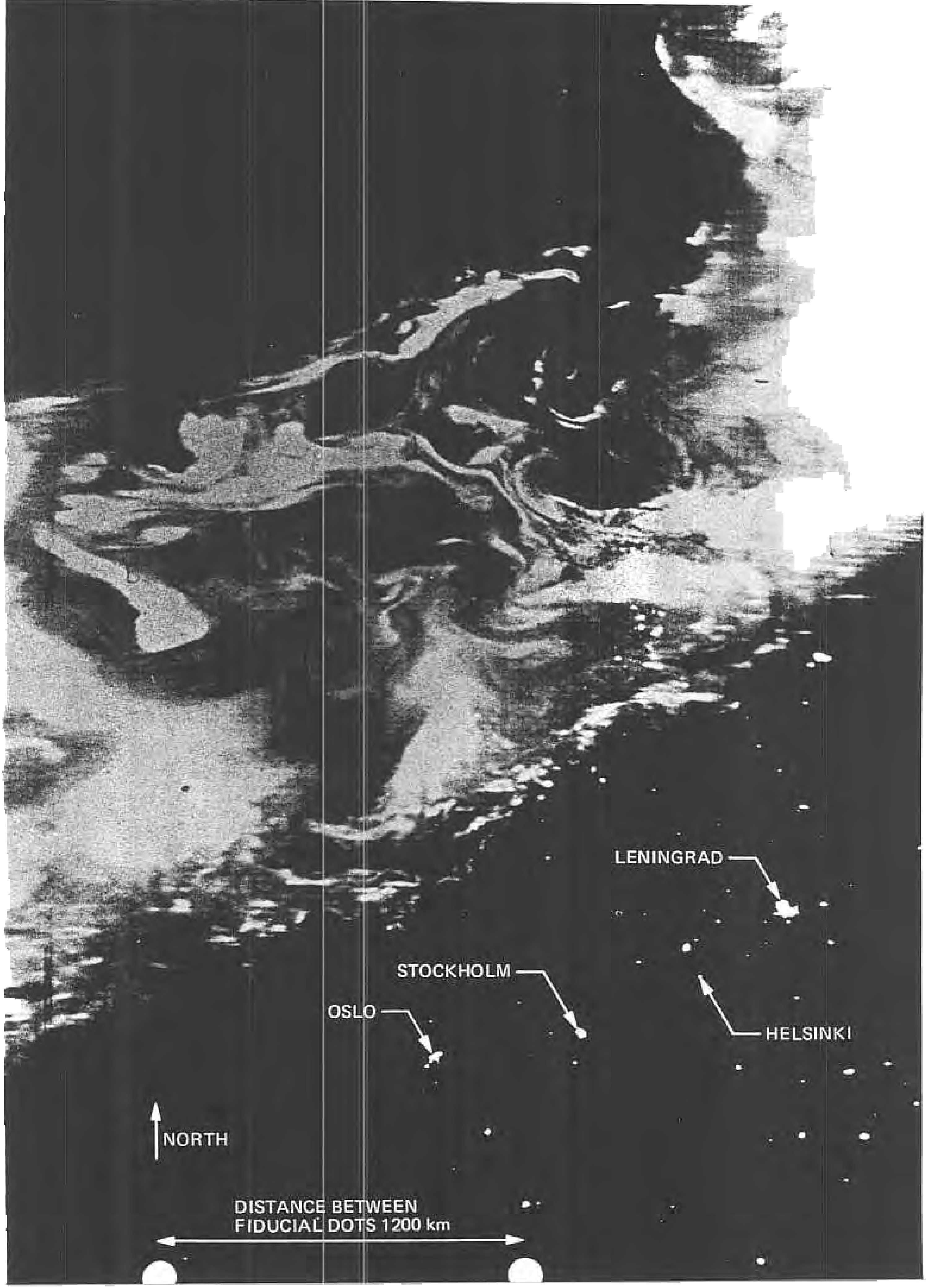
Report of the NASA Plasma Turbulence Explorer Study Group

September 1980

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Cover - This picture is made by a DMSP satellite over northern Scandinavia which has "photographed" the auroral oval during a period of intense turbulent activity. The auroral oval is clearly seen extending from the left side to the upper right side, about 1000 km wide and 3000 km across. During inactive periods the oval is filled with long straight auroral arcs but during active periods the straight arcs act as tracers of large scale turbulence by becoming bent and distorted. The reader may wish to compare this picture with that produced by pouring cream in a coffee cup. Taken from Kelley and Kintner, Ap. J., 200, 339, 1978.


LENINGRAD
STOCKHOLM
OSLO
HELSINKI
NORTH
DISTANCE BETWEEN
FIDUCIAL DOTS 1200 km

715-18

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Preface

The following report is the result of deliberations undertaken at the invitation of Dr. George P. Newton of the Solar-Terrestrial Office of the National Aeronautics and Space Administration. Our charge was to explore some possibilities for and problems associated with a projected Plasma Turbulence Explorer Program or Mission (sometimes abbreviated as PTEP or PTEM in what follows).

It is somewhat of a new departure to undertake the study of a space exploration with a basic physical process as the object of primary interest, rather than its manifestations or realizations in specfic solar-terrestrial locations. We are provided thereby with a new freedom to introduce basic physics in a central role, but we are also forced into a (sometimes humbling) consideration of just what it is that basic physics can contibute. *Pro forma* allusions to its possibilities, after the fact of an already planned mission, are no longer sufficient. We have, however, benefited from some discussions with mission-planning representatives from JPL.

Our recommendations appear in Section VI, at the end of the summaries of the deliberations we have been through before they were reached. Insofar as possible, we have tried to state them in a way that is independent of the details of Sections I through V. It is not our intent, however, that these recommendations be either advocated or adopted without an attempt to understand something of the processes by which they were reached. They are in no sense conclusions which are beyond debate.

I. INTRODUCTION

Under most circumstances, naturally-occuring fluids such as air or water display complex, apparently disordered motion, called "turbulence." Space plasmas are no exception: complicated variations of the electromagnetic field and mechanical field variables in space have been measured at virtually every imaginable spatial scale between meters and AU.

Any serious study of astrophysical fluids must confront turbulence as an important factor. The direct study of plasma turbulence in the local space environment will constrain and shape our understanding of more distant fluids.

The problem of providing a tractable mathematical framework into which collected data can be fit has been a difficult task in fluid turbulence. Even more difficult has been the task of extracting valid theoretical inferences from that framework. The process has spanned almost a century and is far from complete. It is not reasonable to expect the study of space plasmas to be a less demanding undertaking, because a plasma can do everything a neutral fluid can do, plus a great deal more. Any investigator of plasma turbulence needs to maintain an awareness of the difficulties of its fluid antecedents, if only to avoid the certain labor of rediscovering them.

Turbulent phenomena provide the most exhilarating challenges in the theory of classical continua. Two features provide the essential complications in any study of turbulence: (1) the data are for all practical purposes both random and irreproducible, so that the only features which possess any smoothness or regularity are various kinds of averages: over time, over space, over ensembles of realizations; and (2) the basic dynamical equations which are believed to govern the turbulent phenomena are nonlinear and too complicated to solve, except in rather special cases. Item (2) is exacerbated by the fact that because of the highly disparate spatial scales which must be retained, accurate numerical solution is still prohibitively difficult except in the simplest cases.

In responding to questions of the advisability of undertaking a program to study turbulent phenomena in space, it may seem clear that the answer is

"Yes," but it will not do to avoid trying to answer the question "Why?" At present, it would seem that two satisfactory answers can be offered: for practical benefits or for intellectual satisfaction. It is important to be clear at the outset which answer one is giving. If the goal is practical benefits, one is obliged to suggest what they might be. If the goal is intellectual satisfaction, then the criteria of traditional mainstream physics - quality of logic, economy of mathematical statement, novelty, clarity - must become the yardsticks by which contributions and initiatives are measured. Scientifically, something of a fresh start is implied. It should not be taken for granted, at such a critical juncture, that because a particular jargon, style, or set of JGR papers are already in place, they should necessarily dictate the tone for what follows.

As far as practical applications for such a program go, it appears that there might be at least two which are imaginable in the foreseeable future. First, there has been proposed a tantalizing but not yet clear possibility of a connection between solar activity and terrestrial weather and climate. It is not far-fetched that a study of solar, solar-wind, and magnetospheric turbulence might ultimately make that connection clear. Second, communications in the near-earth environment are affected considerably by ionospheric activity; and, in particular, many military possibilities may well include artificially induced turbulence in the near-earth environment that is fearsome to contemplate but should not be ignored. The arguments for pursuing both these applications are compelling but probably not overwhelming. The solar-weather connection awaits the arrival of the first really good idea, and the defense agencies may well be already committed to exploration of the subject of ionospheric turbulence. A possible spin-off of such investigations might also be applications to the turbulence present in controlled fusion confinement experiments.

More reasonable, as a basis for an exploration of space-plasma turbulence, would seem to be a more classically scientific one: the phenomenon is ubiquitous, rich, ill-understood, and represents the manifestation of as-yet-undiscovered laws of nature. The history of physics leads one to believe that major conceptual advances are most likely to occur when such challenges are formulated in their starkest and simplest terms.

Plasma turbulence in space is virtually everywhere and there are probably few measurements in the solar-terrestrial environment which have been reported which do not reflect some kind of turbulent behavior. Even though the presence of turbulent activity often gets in the way of an accurate mathematical calculation of the phenomena, this does not prohibit development of a certain kind of understanding of these phenomena. This has already been for some time an implicit item on the agenda of space science, and is a valuable activity to continue. It should be distinguished, however, from an inquiry into the nature of turbulence itself, considered as a physical process. Since turbulence is ubiquitous in space, careful selectivity needs to be exercised as to which experiments to do and where to go. A hydrodynamic expedition to study turbulence in an oceanographic setting probably would be ill-advised to consider the problem from the point of view of cartography, going to all the seven seas and sampling everything - even though each of the seven seas might be interesting in its own right and have its own constituency. We hope here to establish a basis for some selectivity.

The following report begins with Section II, with what we hope are some not-too-obvious preliminaries relating to the present extent of development of the theory of fluid turbulence, and common areas of overlap with magnetofluid turbulence. Another part of Section II provides background on Vlasov turbulence. Sections III and IV constitute the core of the report. Section III contains some detailed considerations relating to macroturbulence (length scales $\gtrsim$ an ion gyroradius) in space, and Section IV is devoted to considerations of microturbulence, involving spatial scales $\lesssim$ an ion gyroradius. Section V is devoted to possible considerations which might relate to the initiation of a specific Plasma Turbulence Explorer Mission.

Section VI is a summary of our recommendations

II. THEORETICAL PRELIMINARIES

A. Basic MHD Turbulence

We want to illustrate some possibilities and some problems associated with the quantitative description of a measurable field which is exhibiting turbulent behavior. Formally, most of the framework has been developed by fluid turbulence theorists, but much of it has not as yet found its way into the daily parlance of plasma physicists or space physicists. For illustrative purposes, we consider magnetohydrodynamics and look at the variable magnetic field $\underset{\sim}{B}(\underset{\sim}{x},t)$, where $\underset{\sim}{x}$ is the vector that labels the points in some coordinate frame and t is the time. Many of the same statements will apply also to the fluid velocity $\underset{\sim}{v}(\underset{\sim}{x},t)$ for MHD or Navier-Stokes fluids, or to other vector fields.

A magnetometer ideally measures the continuously varying time history of the components of $\underset{\sim}{B}[\underset{\sim}{x}(t),t]$, where $\underset{\sim}{x}(t)$ is the trajectory of the spacecraft. Unlike measurements made in more deterministic kinds of physics, nobody knows a way to make a space magnetometer read the same history twice. It is this fundamental lack of experimental reproducibility that is the distinguishing feature of turbulence, and it is what requires the introduction of probabilistic methods. Certain obvious similarities in the temporal histories are often recognizable by the eye in similar situations. The whole point of turbulence theory is to render these similarities less subjective, more quantifiable, and as predictable and reproducible as possible. It is also desirable to carry out this program in a language that is, insofar as possible, not contingent upon accidental, parochially defined variables or special jargon.

Nobody knows how to get anything reproducible out of a turbulence measurement without some kind of averaging. The averaging may be over time, over space, over several instruments, or over a theoretical "ensemble" of many similar systems. Ensemble averaging is usually implied in theoretical discussions, but experimental limitations usually lead to the use of time averages over only a few measuring instruments. An unproved assumption is involved in the replacement of the one by the other for the simple reason that that is the best one can do. All kinds of averaging are usually lumped together by writing a bracket "<>" around those quantities understood to have been averaged. Mathematically, what one does is equivalent to adopting the point of view that $\mathbf{B}(\mathbf{x},t)$ or other fields of physical interest, are random fields, with expectation values of functions of $\mathbf{B}$ being indicated by the brackets < >. It is then only the bracketed quantities that are of physical interest, as being the only quantities which have any hope of being related to a deterministic theory.

Homogeneity, Isotropy, Stationarity, Reflection-Invariance

Turbulent fields can exhibit certain invariances or symmetries which considerably simplify their descriptions. A homogeneous turbulent field is one in which the statistical properties of $\mathbf{B}(\mathbf{x},t)$ are independent of $\mathbf{x}$. An important consequence of homogeneity is that the sequence of expectation values

$$\begin{gathered} \langle B_i(\mathbf{x},t)\rangle \\ \langle B_i(\mathbf{x},t)B_j(\mathbf{x}+\mathbf{r}_1,t+\tau_1)\rangle \\ \langle B_i(\mathbf{x},t)B_j(\mathbf{x}+\mathbf{r}_1,t+\tau_1)B_k(\mathbf{x}+\mathbf{r}_2,t+\tau_2)\rangle \\ \\ \text{etc.} \end{gathered} \tag{1}$$

which contain most of the accessible information about the field, become independent of the absolute spatial location $\mathbf{x}$ and depend only upon the relative spatial separations $\mathbf{r}_1$, $\mathbf{r}_2$, ... The Roman subscripts i, j, k, ... represent Cartesian components of vectors (i=1, 2, or 3, etc.).

Typically, homogeneity is achieved when the turbulent volumes are large and nearly uniform and the boundaries are far away. Homogeneity is always an approximation that is achieved over a limited region of space. Turbulence is always inhomogeneous at the largest spatial scales. Homogeneous fluid turbulence is not easy to achieve in the laboratory, and much naturally-occuring turbulence is strongly inhomogeneous. Virtually all the basic theory to date concerns homogeneous turbulence, because of the great simplifications which the homogeneous assumption leads to. Outlines of this framework of homogeneous turbulence theory are to be found in the now-classic monograph* by Batchelor[1] and the more recent introduction by Tennekes and Lumley.[2]

While homogeneity describes the invariance of the < > averages under translations, <u>isotropy</u>, which is something different, describes their invariance under <u>rotations</u>. If a random solenoidal field $\mathbf{B}(\mathbf{x},t)$ is both homogeneous and isotropic, has $\langle \mathbf{B} \rangle = 0$, and satisfies reflection-invariance (to be described momentarily), then the six independent scalar functions present in the tensor $\langle B_i(\mathbf{x},t) B_j(\mathbf{x}+\mathbf{r},t+\tau) \rangle$ collapse into a single scalar function of a single spatial variable $r = |\mathbf{r}|$. At $\tau = 0$, this function is most conveniently exhibited as the energy spectrum (energy/unit volume/unit wave number), $E_B(k,t)$:

$$\frac{\langle B_i(\mathbf{x},t) B_j(\mathbf{x}+\mathbf{r},t) \rangle}{8\pi}$$

$$\int d^3k \left(\delta_{ij} - \frac{k_i k_j}{k^2} \right) \frac{E_B(k,t)}{8\pi k^2} \exp(i\mathbf{k}\cdot\mathbf{x}). \qquad (2)$$

The function $E_B(k,t)$ describes the partition of energy over magnetic eddy sizes; the "size of an eddy" is $\sim 2\pi/k$. The length scale over which the covariance $\langle B_i(\mathbf{x},t) B_j(\mathbf{x}+\mathbf{r},t) \rangle$ approaches zero is the size of the "energy containing eddies", or more specifically, the longitudinal integral scale L_p

$$L_p = \underline{3\pi} \quad \frac{\int_0^\infty k^{-1} E_B(k,t)\,dk}{\int_0^\infty \dot{E}_B(k,t)\,dk} \qquad (3)$$

L_p is generally small compared to the dimensions of the system and the volume over which the approximation of homogeneity applies; otherwise homogeneous turbulence theory does not apply.

*References for this section appear at the end of the sub-section, on page 8.

A third kind of invariance which leads to considerable simplicity is that of stationarity, or the invariance of the statistics of $\underset{\sim}{B}(\underset{\sim}{x},t)$ under time translations. Stationarity is to be expected whenever turbulence is being continuously generated at a statistically steady rate, as when air flows through a grid in a wind tunnel, and has as its consequence the independence of the hierarchy of expectations in (1) of the value of t. In particular $E_B(k,t)$ itself, in Equations (2) and (3), becomes independent of t. It is this situation (with only a single scalar function, which is time-independent, remaining) to which the theories of cascades and inverse cascades with their power-law behavior for $E_B(k)$, apply.[1,2,3] No significant beginning has been made at generalizing Kolmogoroff-Obukhov[4,5] cascade theory except under the assumptions of homogeneity, isotropy, stationarity, and mirror-invariance. Mirror invariance is a fourth kind of symmetry which we now discuss briefly.

A field which has an intrinsic right-handedness or left-handedness (is not reflection-invariant) is said to be helical. A simple visual model illustrating a non-helical random field would be a box of identical nails of random orientation. A visual model of a helical random field would be a box of right-handed identical screws of random orientation. For a solenoidal velocity field, the helicity is defined as the volume integral

$$H_v = \int d^3x \, \underset{\sim}{v} \cdot \nabla \times \underset{\sim}{v} \qquad (4)$$

and H_v measures the degree and sense of swirliness about the local direction of flow. The magnetic analogue of (4) is the magnetic helicity H_m,

$$H_m = \int d^3x \, \underset{\sim}{A} \cdot \underset{\sim}{B}, \qquad (5)$$

where $\underset{\sim}{A}$ is the vector potential for which $\underset{\sim}{B} = \nabla \times \underset{\sim}{A}$. Magnetic helicity is produced whenever a current is caused to flow along magnetic field lines. It has become likely [6, 7, 8] that magnetic helicity as defined by Equation (5) plays an important role in MHD turbulence, and that under many circumstances, MHD turbulence will not be reflection-symmetric.

To contemplate the reliance that existing turbulence theory has placed upon the various kinds of symmetry is both challenging and sobering for space physics. The quite respectable body of theory that has been accumulating for MHD turbulence, that relies on high degrees of symmetry, may not be applicable to the situations found in space without major conceptual enlargement. Of the four kinds of symmetries enumerated, it may be safe to assume only two, even in the most regular and quiescent specimens available: homogeneity and time-stationarity. There is clear evidence [9, 10, 11] that even in the interiors of the most uniform regions of the solar wind, the presence of an imbedded dc magnetic field $\langle \underset{\sim}{B} \rangle \neq 0$ (in any frame!) introduces preferred directions in space; that it does so for small-amplitude fluctuations is well known. The absence of any systematic measurements of vector potential prohibits a determination of the extent to which MHD turbulence in space may be helical, though perhaps some estimate could be given by using existing data to compute $\langle \underset{\sim}{B} \cdot \nabla \times \underset{\sim}{B} \rangle$ at various locations. This question appears not to have been addressed.[12]

It is important to emphasize that even the simplest predictions of homogeneous, isotropic, reflection-invariant turbulence theory, such as cascade (similarity) arguments, Kolmogoroff exponents, time scales for eddy lifetimes, length scales for dissipation, and so on, have not been generalized to anisotropic or helical situations. There would appear to be no fundamental reason why they cannot be so generalized but there is no obvious way to do it either. Any generalizations will, very likely, have ad hoc and intuitive elements in them which will require extensive numerical tests in order to acquire confidence in. The activity is not one from which quick or comprehensive results are to be expected, and it would be misleading to suggest that there are already sharply-formulated theoretical questions of a fundamental nature in MHD turbulence that a space mission in the near-term future might resolve. But it is also true that the sharp formulation of such questions is of paramount importance, if further precision is to be injected into space physics.

In addition to proceeding at full speed in developing the basic theory, the question of how to collect space turbulence data in a permanently useful way ought to be considered. One ought to try to acquire data in a form which will suggest theoretical initiatives but which is least refracted by the formalism of a specific presently-existing theory or the individualities of a particular location in space. In this light, it would appear that the covariances and expectation values that begin the chain enumerated in (1) are the most useful quantities: $\langle \mathbf{B}(\mathbf{x},t)\rangle$ and $\langle \mathbf{B}(\mathbf{x},t)\mathbf{B}(\mathbf{x}+\mathbf{r},t+\tau)\rangle$, for all $r>0$ and all $\tau>0$. Any theory that is ever formulated will, if it has any utility, involve these two quantities. If it turns out that there are important cases where the four enumerated symmetries apply, then the Fourier transforms of the covariances will be the spectra of interest. If, as is likely, the various symmetries such as isotropy and mirror-invariance turn out not to apply, then these expectations, and in particular the two-point covariances such as $\langle \mathbf{B}(1)\mathbf{B}(2)\rangle$ and $\langle [\mathbf{B}(1)-\langle \mathbf{B}(1)\rangle]\ [\mathbf{B}(2)-\langle \mathbf{B}(2)\rangle]\rangle$, still give* a crude but useful characterization of the turbulent fields. Among the quantities which these characterizations will include are: (1) r.m.s. values of the fluctuations; (2) the correlation lengths, L_p, or distances that one has to separate the two spatial points in the various directions in order that the covariances shall approach zero; and (3) the correlation times τ_c at which the time points must be separated to make the covariances approach zero. These last two quantities measure the eddy size and eddy lifetime for the "magnetic eddies", an immediately obvious generalization of the corresponding hydrodynamic concept. The value of L_p as a function of angle between $\mathbf{r}$ and $\langle \mathbf{B}\rangle$ in a coordinate frame in which $\langle \mathbf{v}\rangle = 0$ is perhaps the first quantity to which any quantitative theory of anisotropic MHD turbulence might want to address itself.

How such functions as $\langle \mathbf{B}(1)\rangle$ and $\langle \mathbf{B}(1)\mathbf{B}(2)\rangle$, which assume fixed locations in space are to be related to measurements at the location of a spacecraft, moving relative to the plasma in which it is imbedded, is only simple in one case: the case in which the flow speed V_o of the plasma is so large that L_p/V_o is $\ll \tau_c$. In this case the "frozen flow" hypothesis of G. I. Taylor[2] applies, and one may satisfactorily approximate $\langle \mathbf{B}(\mathbf{x},t)\mathbf{B}(\mathbf{r}+\tau\mathbf{V}_o,t+\tau)\rangle$, which is what is measured by a uniformly moving

*Here, $\mathbf{B}(1)$ is shorthand for $\mathbf{B}(\mathbf{x}_1,t_1)$, etc.

spacecraft, by $\langle \underset{\sim}{B}(\underset{\sim}{x},t)\underset{\sim}{B}(\underset{\sim}{x}+\tau \underset{\sim}{V}_o,t)\rangle$, which is what the simplest theory refers to. Not many situations involve relative speeds of spacecraft and plasma that are high enough to make the frozen flow hypothesis well fulfilled. The fact that it is reasonably well fulfilled in the solar wind well ahead of the bow shock is one reason for considering that region as a desirable location for a measurement

In summary, one may say that a relevant body of lore, mathematical formalism, sharp vocabulary, and computational technique has arisen in the century during which fluid turbulence has been studied in a fundamental way. It is difficult to imagine alternative frameworks that depart very far from the ones the fluid turbulence theorists have introduced. These frameworks are in the process of being generalized and adapted to magnetofluids, though the process is slow and the community involved in the process is still small. It does not appear to be an obviously easy task to inject the little insight that has been worked out into the considerations of experimentalists and engineers, or to re-direct attention toward this more abstract perspective. Finally, it is important to realize that progress has been made primarily in those situations in which a very high degree of symmetry can be assumed. Before the methods can be applied conclusively to any space measurements, at least one of two things will have to happen: (1) the assumptions of symmetry will have to be shown to be valid for some space situations, or (2) the theory will have to be generalized in ways that make the assumptions of symmetry less restrictive. Pending the achievement of one of these, probably the best that a basic plasma turbulence mission can do will be to collect data on mean fields, correlations, and covariances, and to represent these data in as theoretically simple a framework as possible.

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12 For a general discussion of magnetic helicity, see: H.K. Moffatt, Magnetic Field Generation in Electrically Conducting Fluids (Cambridge, Cambridge University Press, 1978).

B. Phenomenological MHD Turbulence

Fluid turbulence theory divides at an early stage into a group of basic investigations which direct intensive attention to universal behavior of turbulence with high degrees of symmetry, and a larger group that tries to study real flows in practical cases. So far magnetohydrodynamic turbulence theory is virtually all of the "basic" variety, and it is worthwhile to inquire as to what the possibilities might be for paralleling the "applied" kind of hydrodynamic program.

The methodology can be illustrated by a simple example, drawn from the subject of Navier-Stokes fluids. The flow velocity $\underset{\sim}{v}(\underset{\sim}{x},t)$ evolves according to

$$\frac{\partial \underset{\sim}{v}}{\partial t} + \underset{\sim}{v} \cdot \nabla \underset{\sim}{v} = -\nabla \left({}^{p}/_{\rho}\right) + \nu\nabla^2 \underset{\sim}{v}, \qquad (6)$$

where $\nabla \cdot \underset{\sim}{v} = 0$. (The pressure is p, and the (uniform) density is ρ.) One may represent the field variables, for a steady flow, as a time average plus a fluctuation. Thus $\underset{\sim}{v} = \bar{\underset{\sim}{v}} + \delta\underset{\sim}{v}$, where the bar indicates a time average and $\delta\underset{\sim}{v}$ is the fluctuation. Time averaging Equation (2) for large times gives an averaged version of the Navier-Stokes equation, but the nonlinearities lead to averages of products, which do not go away, such as
$\nabla \cdot \overline{(\delta\underset{\sim}{v} \ \delta\underset{\sim}{v})}$.

This "Reynolds stress" is not a function of $\bar{\underset{\sim}{v}}$ alone, and so the averaging process leaves one with more unknowns than equations. To get back to a framework which is deterministic, one can try to infer approximate expressions which enable one to replace $-\overline{\delta\underset{\sim}{v} \ \delta\underset{\sim}{v}}$ by some function of $\bar{\underset{\sim}{v}}$ alone, such as $\underset{\approx}{\nu}_T \cdot \nabla \bar{\underset{\sim}{v}}$, where $\underset{\approx}{\nu}_T$ is some turbulent visçosity, or "eddy viscosity", which may itself depend upon $\bar{\underset{\sim}{v}}$. The idea is that the fast variations act parasitically on the mean flow $\bar{\underset{\sim}{v}}$ in the same way that an enhanced viscous term would act. Guessing some expression for $\underset{\approx}{\nu}_T(\bar{\underset{\sim}{v}})$ leads back to a computable equation for $\bar{\underset{\sim}{v}}$, the results of which may then be compared with experiment. The modeling may be refined indefinitely.

This class of activity is itself a big industry. A good introduction to it is provided by the monograph of Launder and Spalding.* It and its refinements are what the engineering side of turbulence research is all about. One rather important feature of this class of investigation has been the detailed interplay between theory and experiment and the continual revision of theories which, when extrapolated outside the regime for which they were designed, seem often to fail. The striking thing about the methods would appear to be their situation-dependence and lack of universality.

Even though much has been done along these lines in fluid mechanics, very little has apparently even been attempted for MHD. The structure of the MHD equations closely parallels that for Navier-Stokes fluids, and one may wonder if the activity might profitably be undertaken of taking over into MHD the methods presented, for example, by Launder and Spalding.

The answer would appear to be yes, in general. But when one comes to the specific case of space physics, the indications are far less clear. The reasons concern the inclusiveness of the data that seem to be required. Global and controllable diagnostics seem to play an important part in the calculations which have been done, which concern such engineering situations as flow within channels and ducts, and around corners - situations with relatively clean and simple geometry. Pointwise measurements of the fluid variables over the entire flow seem to be an important ingredient in validating any model. The kinds of data used do not seem to be the kinds that are likely to be realized in space physics in the foreseeable future.

The field is one that surely should be opened up and examined by modellers of the magnetosphere, or of solar wind flow. It might, however, be misleading to advertise a large payoff from this activity in the near future.

*B. E. Launder and D. B. Spalding, Mathematical Models of Turbulence (New York, Academic Press, 1972)

C. Microturbulence

The preceding two subsections dealt with the theory of plasma turbulence as expressed in fluid-like, or macroscopic, variables. It is also possible to formulate plasma turbulence theories in terms of particle distribution functions in phase space. Again, these field variables can be divided into averages and fluctuations. Although the problem is more difficult when formulated in this way, because the number of independent variables has jumped from four ($\underset{\sim}{x}$,t) to seven ($\underset{\sim}{x}$, $\underset{\sim}{v}$, t), it is also true that it provides the ultimate possibility of describing many phenomena which disappear altogether in the fluid limit: those with spatial scales smaller than the gyroradii. The following is a brief introduction to the description of microturbulence.

Introduction to Space Plasma Microtheory

Most solar wind and magnetospheric plasmas are collisionless; that is, mean free paths are of the order of or longer than the scale lengths of macroscopic change in the plasma. In such plasmas, most phenomena are thought to be well described by Maxwell's equations coupled with the Vlasov equation. This equation

$$\frac{\partial f_j(\vec{x},\vec{v},t)}{\partial t} + \vec{v}\cdot\frac{\partial f_j}{\partial \vec{x}} + \frac{e_j}{m_j}\left[\vec{E}(\vec{x},t) + \frac{\vec{v}\times\vec{B}(\vec{x},t)}{c}\right]\cdot\frac{\partial f_j}{\partial \vec{v}} = 0$$

determines the time development of $f_j(\vec{x},\vec{v},t)$, the jth species distribution function. The electric and magnetic fields are obtained from Maxwell's equations which involve the charge and current densities which, in turn, depend on the distribution functions. The Vlasov equation is therefore a nonlinear partial differential equation in seven independent variables.

In a magnetized plasma the ion gyroradius constitutes a natural division between longer and shorter wavelength fluctuations; we denote the two phenomena by the prefixes "macro-" and "micro-", respectively. Collisionless macrophenomena are well described by Maxwell's equations coupled to a set of fluid equations which are functions only of space and time and which may, under suitable assumptions, be derived from the Vlasov equation.

In contrast, most collisionless microphenomena require the velocity space information of the Vlasov equation for their complete description; this additional information implies that the physics of microphenomena is much more diverse than that associated with macrofluctuations. In particular, the Vlasov description introduces a phenomenon which is unique to plasma physics: the wave-particle interaction. This interaction allows the exchange of energy among the fluctuations and the various plasma particle species and leads to phenomena (generally known as Landau damping or growth) which cannot be described by a set of fluid equations.

"Turbulence" means that the fields and plasma parameters have fluctuating components with random properties which require a statistical description. Fluctuations are regarded as turbulent if they have appreciable amplitude over a broad range of wave numbers $\Delta\vec{k}$. Specifically, $|\Delta\vec{k}| \sim k$ where k is some wave number of interest. Such broad spectra are usually what is observed in space; this is the basic justification for treating space plasma fluctuations as stochastic, particularly if the phase correlations between the different $\underset{\sim}{k}$'s are weak.

In discussing microfluctuations, it is necessary to distinguish between weak and strong turbulence. One condition necessary for turbulence to be considered weak is that the energy density of the fluctuating fields

$$\mathcal{E} \equiv (|\delta E|^2 + |\delta B|^2)/8\pi$$

must be much less than the thermal energy density of each plasma species, nk_BT_j.

But there is a second, more difficult condition to be met. If at a particular wavevector $\vec{k}$ there are enhanced microfluctuations over a range of frequencies $\Delta\omega$ that is narrow compared to the characteristic frequency ω, i.e., $\Delta\omega \ll \omega$, then the concept of a dispersion relation relating frequency and wavevector is a valid one and the fluctuations are said to be weakly turbulent. If $\Delta\omega \gtrsim \omega$, there is no dispersion relation and plasma modes as such do not exist; the turbulence is called strong. Figure 2-1 suggests a way of observing the difference between the two types: for a given wavevector $\vec{k}$, the frequency spectrum of the fluctuating field energy density, $S(\omega)$, is very broad for strong turbulence and clearly peaked for weak turbulence.

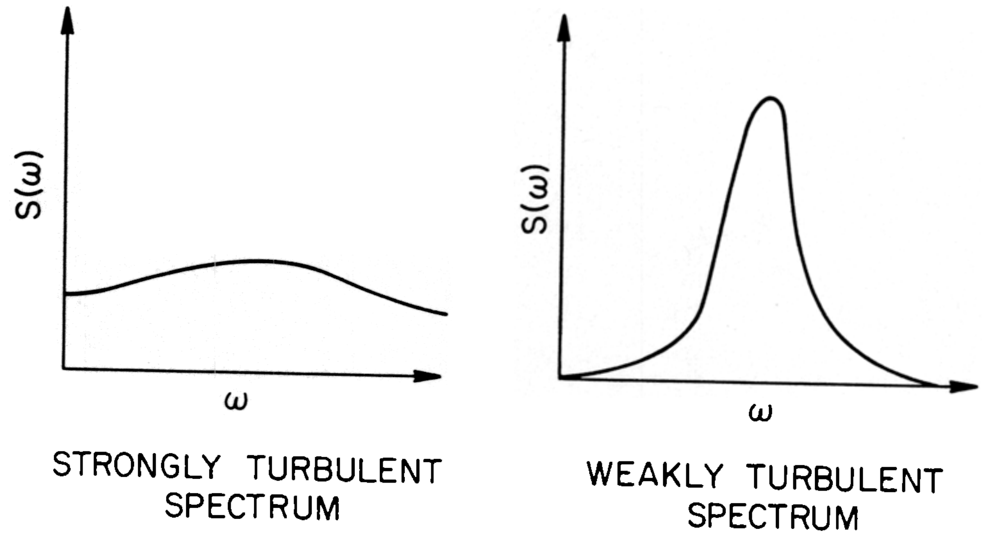

Figure 2-1

Plasma macroturbulence is usually strong. Space plasma microfluctuations usually satisfy $\mathcal{E} << nkT$, but observations have not yet resolved frequency spectra with accuracy sufficient to determine whether most types of microturbulence are, in fact, weak.

The theoretical description of macroturbulence has concentrated on the fully nonlinear properties of the associated fluid equations. In contrast, the complexity of the Vlasov equation has limited much microtheory to the weak turbulent regime where perturbation expansions may be used. Strong microturbulence, involving the dual challenges of a fully nonlinear theory and a very complex equation, has received less attention, but may be viewed as an ultimate goal which may be obtained through understanding of the other two regimes.

Weak Microturbulence. Since wave-particle interactions are fundamental to microphenomena, research in this topic must address both fluctuating fields and particle distributions. A framework in which both theory and experiment can study weak microturbulence in a self-consistent way is shown in Figure 2-2.

To construct a weak microturbulence theory, the plasma fluctuations must satisfy conditions in addition to those discussed above.

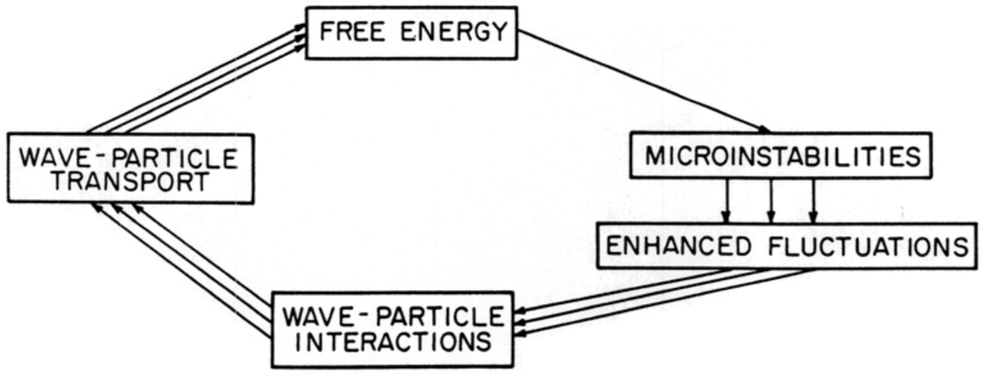

Figure 2-2

A general criterion is that the spatial and temporal rates of change for macroscopic quantities be much slower than those of microquantities. Macroscopic scale lengths are, by definition, longer than microwavelengths, and in general the periods of macrophenomena stand in the same relation to microfluctuation periods. What is necessary for a microtheory is a clear separation between the macro and microscales.

Consider the fluctuation energy spectrum as a function of wavenumber. If wave-wave interactions dominate, the important physics is the transfer of energy among wavenumbers, and as shown on the left hand side of Figure 2-3, there is no such separation. However, if wave-particle interactions are more important, the interaction of the distribution functions with a narrow range of wavenumbers produces enhanced fluctuations with a relative maximum in the wavenumber spectrum as shown in the right hand side of Figure 2-3. Then the separation between macro and microscales is clear, and macroscopic quantities may be taken to be stationary on the micro time scale and weakly inhomogeneous on the ion gyroradius length scale.

Then, using the fluctuating field amplitude as a small parameter, a perturbation expansion of the Vlasov equation may be carried out. To first order one obtains the linear Vlasov equation which may be solved by a conventional Fourier-Laplace analysis; the solution yields a variety of plasma modes with amplitude proportional to $e^{-i\omega t}$ where ω is a complex frequency $\omega = \omega_r + i\gamma$. The frequency of each mode is a unique function of wavenumber, $\omega(\vec{k})$, which is determined from a linear dispersion relation. If the zero order distributions are uniform Maxwellians, the modes are damped in time ($\gamma < 0$). If one or more of the distributions is nonuniform or non-Maxwellian, there is free energy in the plasma which can allow fluctuations to increase in time ($\gamma > 0$). Such growing fluctuations are called a plasma instability; the minimum conditions necessary for growth are called instability thresholds.

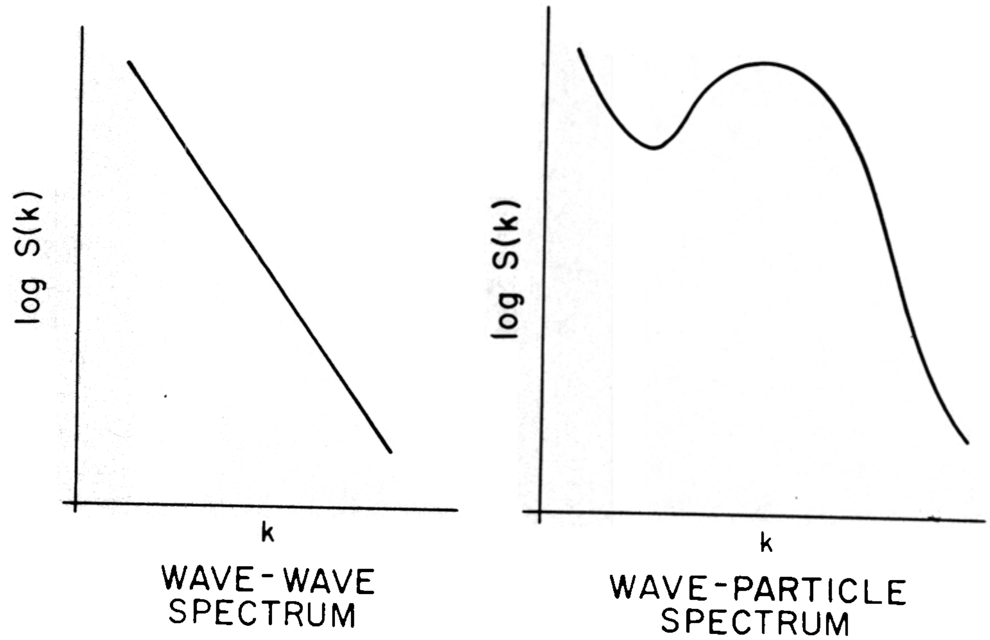

Figure 2-3

Each free energy source, for example, temperature anisotropies, density gradients, currents or flow shears, may give rise to several different instabilities, each with its own threshold, its own $\omega(\vec{k})$ and its own dependence on the various plasma parameters. So a modest industry has grown up around the identification and classification of species in the instability "zoo".

However, since micro-time scales are much faster than macro-times, the linear growth phase does not make an important contribution to the macroscopic plasma behavior. Rather, soon after the instability undergoes its rapid growth, nonlinear or other dissipative physics act to balance the linear growth and the fluctuating fields attain an enhanced, saturated level. Wave-particle fluctuations scatter plasma particles and yield transport which tends to reduce the source of free energy; thus the self-consistent picture of Figure 2-2 is made complete. In general, the rate of macroscopic change associated with this transport is much slower than the microscopic growth rate, as shown in Figure 2-4. If this rate is sufficient to drop the free energy below the instability threshold, the fluctuations are no longer driven and quickly fall back to lower levels (see Figure 2-4).

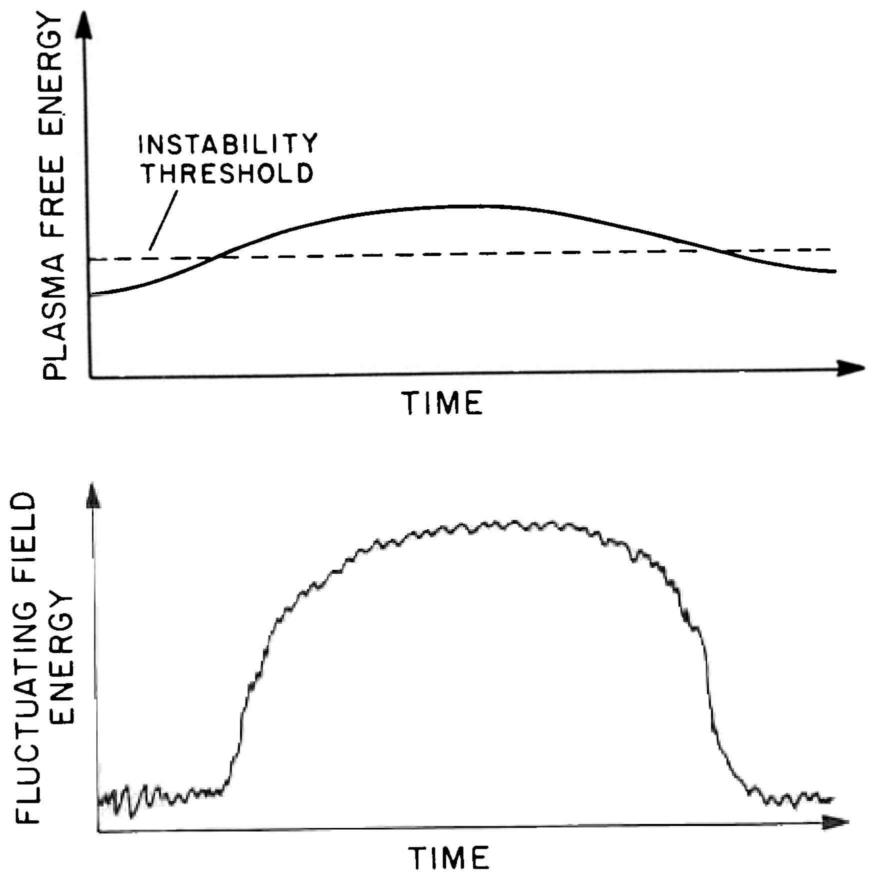

Figure 2-4

Although the linear aspects of most microturbulence theories are based on the general conditions discussed above, the nonlinear calculations of wave-particle transport utilize a variety of different techniques and may reach a multitude of different conclusions. Here we illustrate one procedure which, by requiring the satisfaction of one additional condition, permits a self-consistent computation of wave-particle transport.

The wave-particle resonance velocity is that velocity at which a particle most strongly experiences the influence of a plasma wave; the typical example is the Landau resonance at $v_z = \omega/k_z$ where $\hat{z}$ is the direction of the ambient magnetic field $\vec{B}$. This quantity may be calculated by using the values of ω and k_z from the linear dispersion relation which correspond to significant growth rates of an instability. The range of values of ω/k_z determines the nature of the wave-particle interaction of a particular species with a particular instability; the possibilities are illustrated in Figure 2-5.

Many weak turbulence theories have been formulated on the basis of relatively narrow wave-particle resonances. Such an interaction, it is assumed, leads to significant changes in a narrow velocity regime of the distribution function. However, the narrow changes predicted by such quasilinear theories are not often observed in space plasma velocity distributions.

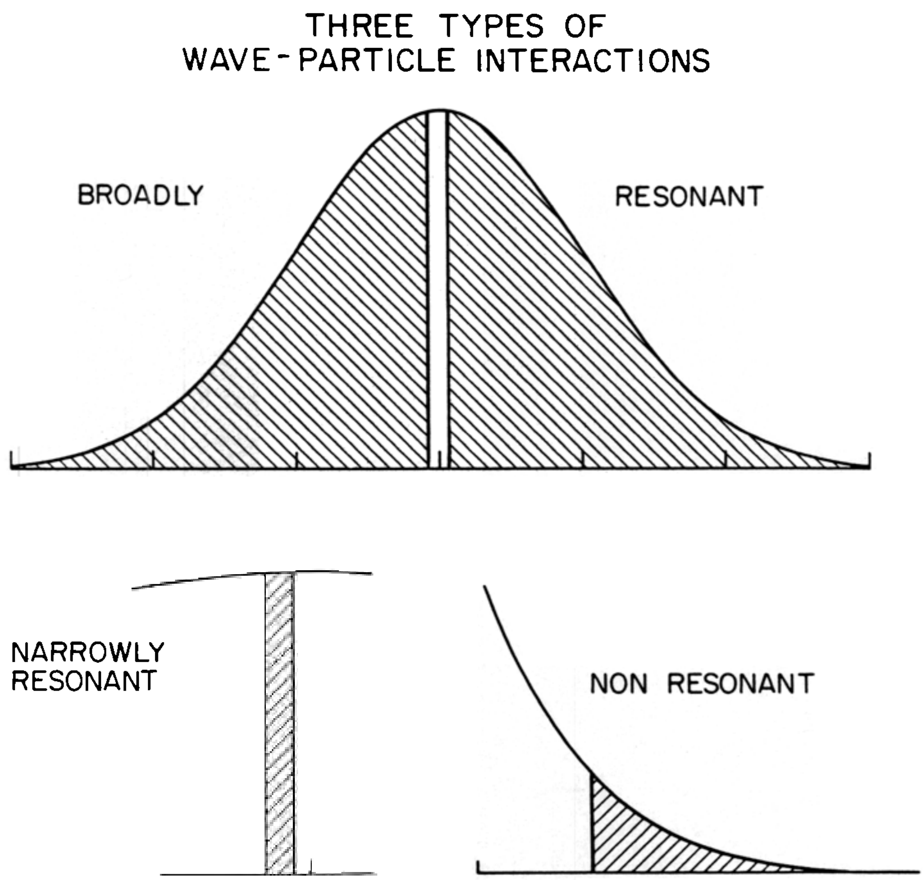

Figure 2-5

Thus the additional condition of this procedure: there is a broad wave-particle resonance with the species which drives the instability. If this condition is satisfied, wave-particle interactions affect most particles of the driving species; the implication is that the physics of this interaction is well described through the use of velocity moments of the distribution (e.g., densities, average velocities, temperatures). One then expands the Vlasov equation to second order and averages over an ensemble of fluctuations with random phases to obtain the equation governing the slowly varying part of the second order distribution function of the resonant species. Taking the first and second velocity moments of this equation yields concise equations which describe the time rate of change of momentum and energy of the resonant species. These rates are written as the sum over the wavenumber spectrum of a factor involving the resonant species contribution to the linear dispersion relation times the fluctuating field energy density $\mathcal{E}$.

To evaluate these wave-particle exchange rates, one must obtain expressions for the maximum or saturated value of $\mathcal{E}$. The broad diversity in microphenomena extends to the mechanisms responsible for saturation of $\mathcal{E}$; in different physical situations there are a variety of possibilities. For high frequency ($\omega_r \gtrsim \Omega_e$), high phase velocity instabilities such as those driven by electron anisotropies, convection of wave energy out of the unstable region may determine the maximum field amplitude. For non-dispersive instabilities, i.e., ω_r = (constant) k, or electron beam instabilities, wave-wave coupling can be an efficient process of energy transfer in wavenumber space and may be the saturation mechanism. For relatively low frequency, dispersive instabilities such as those driven by a current, heat fluxes, or cross-field shears or gradients, nonlinear wave-particle mechanisms variously referred to as "trapping", "resonance broadening" or "orbit modification" are the likely means for determining the maximum fluctuating fields. If the instability is driven by a broadly resonant species, there is likely to be another species which is nonresonant or narrowly resonant. Nonlinear resonance broadening does not significantly alter the already broad wave-particle interaction, but it does bring additional particles of a nonresonant or narrowly resonant species into resonance, thereby increasing the damping until saturation is reached.

Using the $\mathcal{E}$ calculated from an appropriate theory, and evaluating the contributions to the linear dispersion relation by use of the appropriate $\omega(\vec{k})$, one can evaluate the resonant particle wave-particle momentum and energy frequencies. The resonant particle heating rate then follows, and conservation of momentum and energy then yield the corresponding quantities for the nonresonant species.

When these exchange frequencies are evaluated in this way, they are independent of microscopic properties and depend only on the macroscopic or fluid parameters of the plasma: density, average velocities, temperatures, etc. Thus they may be immediately used in a fluid model computer calculation describing the macroscopic evolution of the plasma. Such a calculation, of course, will describe the development of the free energy source driving the instability so that the self-consistent loop pictured in Figure 2-2 is thereby made complete.

The picture we have drawn here has used a single source of free energy, but a real plasma may have several such sources. Then it is necessary to repeat the above process for each instability which may arise in the plasma and calculate the appropriate wave-particle exchange frequencies for each. A rule of thumb for wave-particle transport is that the primary result of wave-particle interactions due to enhanced fluctuations from a particular instability is to reduce the source of free energy which drives that instability. But secondary results can affect other free energies so that a full understanding of weak microturbulence requires full cooperation between analytic theory and computer fluid models.

This self-consistent picture of microturbulence transport theory requires the existence of a wave-particle fluctuation spectrum as shown in Figure 2-3, so that there is a clear separation of the micro- from the macro-physics. If, in contrast, there exists a wave-wave spectrum which extends across the ion gyroradius, micro- and macrotheory must be coupled in order to provide a complete description of the plasma. As an illustration, consider a situation in which the spectrum amplitude is determined by a balance between energy input by spectral cascade from the macroscopic fluctuations and damping due to microscopic wave-particle interactions. In such a case one may compute the microscopic contribution to turbulent transport (using, in effect, only the bottom half of Figure 2-2) and obtain a wave-particle resistivity and viscosity that can be returned to the macroscopic theory as dissipation rates for the short wavelength turbulence.

Strong Microturbulence. If the weak turbulence condition, $\Delta\omega << \omega$, is not satisfied, then more difficult strong turbulence theories must be used to describe the fluctuations. In this regime neither the Laplace analysis in time nor the perturbation expansion of weak turbulence may be carried out. Thus in strong turbulence it is necessary to solve fully nonlinear partial differential equations; much of the progress in this regime has therefore been made through the use of nonlinear computer programs called particle simulation codes.

In these codes a small portion of the plasma is represented by a macro-particle. The behavior of the plasma is studied by using the computer to advance a large collection of macroparticles in time according to the basic force equations. The force field in the equations is derived using the spatial distribution of macroparticles. Although the results of a given computer simulation tend to be dependent upon the initial and boundary conditions, a number of general properties characterizing strong electrostatic plasma microturbulence have been learned from these simulations.

In strong turbulence radiation pressure plays an important and fundamental role in the plasma dynamics. The reason for this is that the plasma density is modified by gradients in the electric field energy density. The wave energy tends to concentrate in regions of low density leading to increased radiation pressure which further enhances the density depression. The result is that strong turbulence is characterized by highly localized, very intense electric fields and density fluctuations. The spatial scale of these nonlinear structures is tens of Debye lengths. The highly localized fields lead to energization of a somewhat select group of plasma particles typically leading to high energy "tails" in the velocity distribution, so that the velocity distribution is not well characterized by a temperature.

The nonlinear structures in strong turbulence can be somewhat understood analytically in terms of envelope solitons. There are highly localized solutions to the small amplitude nonlinear equations. These structures may play a fundamental role in strong microturbulence much as eddies play a fundamental role in fluid turbulence. Although the theoretical basis of strong microturbulence is not well advanced at this point, it appears that the theory of strong microturbulence may require an entirely different approach from that used to study fluid turbulence or plasma macroturbulence.

III. REPORT OF THE MACROTURBULENCE SUBCOMMITTEE

It is clear from observations that the rarefied plasmas of astrophysics fluctuate irregularly both in space and in time. In many cases of interest the root-mean-square fluctuation of, say, intensity of magnetic field is comparable to the mean of the same quantity, implying that the fluctuations, or turbulence, are strong. It may be remarked parenthetically that the existence of turbulence in these plasmas is not unexpected, because any relevant "Reynolds number" is extremely large. Direct observations have shown that astrophysical and geophysical fluids, whether on the surface of the earth, in its atmosphere or the atmospheres of other planets, or the plasma environment of geospace and interplanetary space, exhibit power spectra that are power laws in wave number with indices close to that given by the Kolmogorov spectrum.

There is a growing body of observational evidence of turbulence in the interstellar medium, with irregular fluctuations in various parameters that are comparable to the means. These remote observations indicate that the coherence scale of any interstellar turbulence must be of the order 10-100 pc. Observations of the interstellar gas have measured this correlation function down to scales of the order of 1 pc, and suggest that the power spectrum is taking on a power law character with index of the order -5/3 as smaller wave numbers are approached.* Thus, there is some evidence, although it is not yet strong, for the existence of Kolmogorov's spectrum in interstellar space. One other extremely interesting piece of information is the fact that interstellar scintillations of pulsar signals provide an estimate of the fluctuations at scales of the order 10^{11} cm, seven orders of magnitude smaller than the smallest scales observed optically. These estimates of the power are consistent with the extrapolation of a Kolmogorov spectrum. Observations of cosmic rays and other manifestations of the interstellar gas also point to the existence of relatively small-scale turbulence, although the connection is not yet very quantitative. In addition, there is abundant evidence for the existence of turbulence and small-scale fluctuations in many extragalactic radio sources.

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*L. C. Lee and J. R. Jokipii, Ap. J. 206 735 (1976).

Altogether, strong irregular fluctuations appear to be ubiquitous on all scales of interest for geophysics, space physics, and astrophysics. Although these fluctuations are conventionally described as "turbulence", it should be emphasized that our understanding of these fluctuations is on the kinematic level at best. It is appropriate to raise the question of whether detailed observations in space can advance our understanding of the dynamics of astrophysical plasma turbulence. This turbulence is associated with a large range of length scales, generally longward of the local ion gyroradii. Hence the hydromagnetic, or "macroturbulent" regime is of particular interest. This present section is concerned with the opportunities for the study of macroturbulence by in situ measurements in geospace from a dedicated Plasma Turbulence Explorer Mission.

The first part of this section is a general discussion of the scientific objectives, as far as macroturbulence is concerned, for a Plasma Turbulence Explorer Mission (PTEM). Subsequently, we discuss the relevant length and time scales in various regions, instrumentation, radio techniques, current multipoint turbulence studies, and finally the number of spacecraft and their configuration.

A. Scientific Objectives

We anticipate that for many years to come, as in the past, space will be our primary laboratory for the study of collisionless hydromagnetic waves and turbulence. The solar wind, magnetosheath and magnetosphere provide distinct but complementary laboratories for such experiments. Conversely, the large-amplitude waves and turbulence found in these regions are thought to influence the dynamics of the several plasma systems in important ways, and, in the case of the solar wind, to provide important clues about the acceleration of the solar wind near the sun, and the modulation of cosmic rays. A properly designed program of multipoint observations of hydromagnetic waves and turbulence in geospace would result in significant advance both in basic plasma physics and the dynamics of the solar-terrestrial plasma environments.

Solar Wind and Magnetosheath. Dynamical changes in the solar wind occur on all time scales ranging from the period of solar rotation (~27 days) to the proton gyroperiod (~1 sec) and shorter. The solar wind, as observed at the orbit of earth, is typically divided into several large-scale streams which frequently recur from one solar rotation to the next. Despite the general persistence of the stream pattern, and associated magnetic sector structure, the intensity, duration and profile of the streams are not reproducible, but have an apparent random component. It may be that large scale structures, waves, and vortices, are generated in the accelerating and heating phases of the solar plasma, and that partially ordered remnants of these persist as far away as one astronomical unit. Laboratory research in fluid dynamics has shifted away from the study of smaller scale fluctuations to the study of the dynamic and geometric structure of larger eddies, horseshoe vortices, helical vortices, bubble forms and vortex breakdown. It took nearly three decades to find many of the larger flow features in laboratory experiments, in part because smaller scale features may disguise the remnants of more ordered features. Analogous hydromagnetic structures, as yet unidentified, may exist in the solar wind.

Hence, a complete program to study interplanetary turbulence must include investigation of the largest-scale variations. However, such studies imply observations from points separated on a scale ~1 AU. By itself, an Explorer-class mission would provide essentially one point observations of phenomena on this scale. However, by the mid-eighties the International Solar Polar Mission and the Interplanetary Laboratory of OPEN will be operational. Moreover, there may well be an earth-orbiting Solar Corona Explorer, which, together with the coronal imaging from the ISPM, will give a "stereoscopic" view of dynamical events in the corona. A few years later, the Solar Probe Mission should dramatically advance our understanding of the acceleration and heating of the solar wind. Hence it would appear that important measurements of the largest-scale turbulent structures will become possible, and a PTEM could be integrated into the total programmatic picture. However, the main contributions of a PTEM would be to the study of turbulence on a local scale ($\lesssim$0.1 AU $\approx$ correlation length).

Faster solar-wind streams overtake slower streams, producing a broad, disturbed interaction region. The central regions and trailing edges of fast streams are less disturbed, but nevertheless usually contain large-amplitude Alfvenic (noncompressive) fluctuations; in addition, the streams tend to be divided into relatively homogeneous compartments by thin current sheets ("discontinuities"). Data from PTEM by itself would correspond to spatial separations of 0.01 AU or less; these multipoint observations would therefore give detailed information about the spectrum of turbulence on scales small compared with stream size. (These same observations would also provide an excellent opportunity to study the geometry and structure of the interplanetary current sheets and shocks.)

The interplanetary Alfvenic fluctuations have been extensively studied on the basis of one-point (and occasionally two-point) observations. The magnetic field fluctuates in direction but not magnitude, and the plasma density remains constant. The fluctuating components of velocity and magnetic field, and the steady density and field strength of a typical Alfvenic region, are shown in Figure 3-1 (Belcher and Davis, 1971). The correlation between magnetic field and velocity variations corresponds to propagation away from the sun (in the plasma frame). Since the flow is strongly super-Alfvenic, the above correlation provides a strong argument for the solar origin of the Alfvenic fluctuations. Thus these fluctuations are very probably the remnant of a field of Alfven waves or turbulence near the sun, which may be intense enough to play a major role in the acceleration of the wind.

The simplest theoretical picture of the evolution of the Alfvenic fluctuations is that they propagate (and are convected) into the interplanetary medium as waves describable by the WKB approximation. This assumption implies that the wave normal direction (= minimum variance direction of magnetic fluctuations) should be radially outward from the sun; this prediction is not consistent with observation. Refinement of the WKB approach to include realistic stream structure does not improve closure between theory and experiment. The fluctuations usually have a well-defined direction of minimum variance, suggesting that they are locally plane waves; (i.e., that their $\mathbf{k}$ spectrum is peaked along $\pm \langle \mathbf{B} \rangle$). On the other hand, limited two-point observations cast doubt on the planarity of these waves. A definitive resolution of this dilemma could be provided by extensive multipoint observations in the PTEM.

If it turns out that the Alfvenic fluctuations are waves, we are faced with trying to understand why the WKB approximation breaks down. If, on the other hand, the fluctuations are not planar, they presumably are to be regarded as turbulent. In that case, the spectrum of the turbulence must be defined as well as possible. It is not likely to be isotropic (given the typical well-defined minimum variance direction), and the assumption of isotropy cannot be used in defining the spectrum. Knowledge of the spectrum near the orbit of earth should clarify the meaning of one-point observations of turbulence elsewhere in the solar system, thus providing the beginnings of a global picture of interplanetary turbulence.

The hydromagnetic fluctuations of the stream interaction regions, in contrast to the Alfvenic fluctuations, are compressive and therefore probably dissipative and hence generated locally in the interaction region. The large-amplitude, chaotic character of these fluctuations is difficult to incorporate into a simple wave picture, and they are generally described as "turbulent." Studies of these fluctuations from one-point observations have been sketchy, and no theoretical treatment has been presented. Multipoint observations of interaction regions could give the location and orientation of the stream boundary and the profiles of the fluctuating fields as they vary with distance from the boundary. Such a detailed description of the interaction regions would clarify single point observations of such regions at other points in the heliosphere, again contributing to a global picture of heliospheric turbulence, and provide a framework of data to constrain theories of hydromagnetic turbulence.

Fluctuations in the earth's magnetosheath (shocked solar wind plasma behind the earth's bow shock) are also compressive, large-amplitude and chaotic. Operationally, the function of the PTEM in the magnetosheath would be similar to its function in interaction regions. The theoretical context would be different, however. Magnetosheath turbulence is probably produced by the bow shock, and study of this turbulence is part of the study of the whole shock phenomenon. (An earth-orbiting mission capable of measuring interplanetary turbulence would cross the bow shock many times, and provide a unique opportunity for investigation of the shock structure as well. In addition, the mission could provide a complete picture of the generation of waves upstream of the bow shock by reflected charged particles.) In addition, the PTEM would be able to check theories that post-shock fluctuations result from the amplification of pre-shock fluctuations. Finally, the passage of an interplanetary shock while the PTEM array was in the solar wind would provide an opportunity to investigate the geometry, structure and post-shock turbulence of those shocks.

One of the important unsolved problems of astrophysical plasma physics is the transport of cosmic rays (or any energetic particles) through space. The most widely accepted current theory is that scattering by the irregular magnetic field fluctuations acts, in most cases, to drive the angular distribution of the energetic particles toward isotropy. This results in the bulk motion of the particles being in large part diffusive. One major goal of theory has been to relate the scattering of particles to the structure of the magnetic field irregularities. The irregularities are a manifestation of plasma turbulence and their description is most naturally in terms of correlation functions. The most widely used theory up to the present has been the quasilinear approximation. In this, the statistics of the particle motion can be determined in terms of the two-point correlation function of the magnetic field.

$$R_{ij}(\underset{\sim}{r},t) = \langle B_i(\underset{\sim}{r}_1,0)B_j(r_1 + \underset{\sim}{r},t)\rangle$$

The precise form in which the quasilinear result is written varies, but in all cases is essentially equivalent to requiring the integral of $R_{ij}(r)$ along the unperturbed (helical) particle trajectory. In effect, therefore, <u>the theory assumes knowledge of the correlation function</u> of r <u>at a given time</u> t.

Quasilinear theory is but the lowest-order approximation, and it requires that the field fluctuations be small. Higher order theories have begun to appear, and it is likely that they will use higher-order correlations. Hence, current views of cosmic-ray and energetic-particle transport require detailed knowledge of the electromagnetic correlation function. Current measurements give only a straight-line cut through the correlation function, and hence are incomplete. It is not surprising, therefore, that the particle measurements are at variance with theoretical predictions. Hence, direct observation of interplanetary turbulence by PTEM may substantially improve our understanding of cosmic ray transport. In addition, PTEM may produce significant revisions of the current theory of interplanetary fluctuations, with unforeseen benefits for the theory of cosmic ray transport.

Magnetosphere. Interaction with the solar wind results in a circulation of material within the Earth's magnetosphere. This circulation has a well defined mean flow which, roughly speaking, corresponds to sunward flow on closed magnetic field lines in the inner magnetosphere and anti-sunward on the open or stretched magnetic field lines which thread the polar cap. A variety of measurement techniques have been applied to determine this pattern with the result that its basic characteristic is fairly well established albeit not completely understood.

One feature of the flow pattern, which all these measurement techniques have detected, with varying degrees of sensitivity, is that it is extremely turbulent. Use of the term turbulence in this context is in the classical sense of fluid dynamics since it refers to fluctuations in the velocity field $\underline{V}(\underline{r})$ of the medium. Since the perpendicular components of the velocity field and the electric field are related by the relationship

$$\underline{V}(\underline{r}) = c\ \underline{E}(\underline{r}) \times \underline{B}(\underline{r})/|\underline{B}(\underline{r})|^2$$

where $\underline{B}(\underline{r})$ is the magnetic field, measurements of $\underline{E}(\underline{r})$ have also been used to study magnetospheric turbulence. In fact wave electric field detectors allow study of the short wavelength regime with much greater sensitivity than that afforded by direct velocity measurements. This approach is referred to as the guiding center approximation.

Past experimental studies admit several conclusions:

1. Fluctuations in the velocity field are comparable to the mean flow.
2. The flow is turbulent at scales from meters to thousands of kilometers.
3. The perturbation fields are spatial in the sense that they convect with the mean flow.
4. Most the energy exists at the largest scale lengths.
5. Turbulence is observed over wide ranges of latitudes including the auroral zone.
6. Vertical scale heights are the order of horizontal scale lengths.

Taken together these conclusions strongly suggest that the earth's magnetosphere constitutes a laboratory for study of turbulence in a flowing, cosmic scale plasma which is readily accessible to detailed study. Furthermore the range of parameter space in which this turbulence exists is vast-ranging from the cold low beta* ionospheric plasma to the hot, high beta plasma sheet. The ratio of box size to viscous scale length of 10^5 also strongly suggests that the assumptions of homogeneity can be effectively applied to the magnetosphere.

The most intense examples of large scale magnetospheric turbulence occur during periods of active auroral displays. The aurorae begin as long east-west arcs which then act as tracers of turbulent motion in a way similar to cream in a coffee cup. An example of developed turbulence in the auroral zone can be seen in Figure 3-2 which is a photograph of the auroral zone over northern Scandinavia. The fiducial dots at the bottom are 1200 km apart and north is toward the top. In this example turbulent motion is visible from scale sizes of greater than 1000 km to less than 10 km (the resolution of the photograph). The area filled with turbulence is at least 1500 km across and several thousand km long. Photographs of this kind show that large scale turbulence within the magnetosphere is qualitatively similar to neutral fluid turbulence.

Characterization of neutral fluid turbulence has usually started with description of the velocity fluctuation spectrum V(k) and covariances of the

*Beta is the ratio of mechanical to magnetic pressure velocity spectrum $<\underline{V}(\underline{r})\ \underline{V}(\underline{r} + \delta\underline{r})>$. A power law dependence with different spectral indices in different wavelength regimes is predicted and has been found experimentally. General features are that the largest velocities are found at the largest scales, a cascade of wave energy via mode-mode coupling occurs and some dissipation mechanism exists at small scales.

A very preliminary study of V(k) for the magnetosphere was performed by Kelley and Kintner (1977) who combined electric field data from balloons and satellites to produce a spectrum for V(k) extending over 5 orders of magnitude. Several features of the data correspond to two dimensional turbulent spectra, including the break in spectral slope and the detailed spectral indices. The break in spectral slope occurs in the same wavelength regime as that of the auroral folds and curls, structures which are known to be related to flow patterns in the auroral ionosphere. Another prediction of two dimensional turbulence is the condensation of energy into vortices. particle velocity measurements of Hones, et al. (1979) show vortices flowing anti-sunward along the flanks of the magnetosphere in a picture similar to vortex streets.

Although preliminary, these data suggest that the concepts applied to turbulence in two dimensional fluids may be applicable to many magnetized plasmas. Detailed experimental study of the magnetosphere is required to determine if and when the fluid turbulence concepts can be applied to plasmas. The wide ranges of plasma parameters and boundary conditions make the system very attractive for testing either predictive or descriptive turbulence theories and eventually theoretical models for turbulence in a variety of plasma systems.

Recent satellite and rocket measurements have shown that the source for the acceleration of the primary auroral electron beam lies at an altitude of about one earth radius above the auroral ionosphere. An extended electrostatic perturbation exists with large potential drops both parallel and perpendicular to $\underline{B}$. The parallel electric field component as well as the fact that the large perpendicular fields do not map down to ionospheric altitudes shows that classical magnetohydrodynamics break down in this region. The concept of frozen-in magnetic fields thus does not work; and regions of the magnetosphere are decoupled from each other. The decoupling, the associated particle acceleration, and the limitation of field aligned currents may be of fundamental importance to many astrophysical systems.

A variety of associated phenomena in addition to fluid turbulence occur in this region, which include terrestrial kilometric radiation, ion cyclotron waves, and ion beams. The shock-like structures detected in polar orbiting satellite electric field data are invariably imbedded in a region of smaller amplitude electric field fluctuations. These are smaller only in a relative sense since the turbulence has an energy density which is 10% of the total energy density in the plasma. This level is considerably higher than the convection turbulence occurring over the entire polar cap. In fact, this region may be the source for much of the observed turbulence in the magnetosphere since the mean flow pattern moves plasma into and out of the turbulent zone and into the less disturbed portions of the flow pattern.

The turbulence zone has also been detected at higher altitudes and referred to as broadband electrostatic turbulence.

Some examples of crucial open questions include:

1. Is the turbulence a result of the formation of electrostatic shocks, or does it play a fundamental role in their formation?
2. Is it related to an anomalous resistivity perpendicular to the magnetic field?
3. Is the turbulence in magnetospheric convection seeded by the shock region?
4. What are the properties of decaying turbulence in an MHD flow as the plasma convects away from a source of disturbance?
5. What roles do characteristic scales such as the hot and cold ion gyroradius play in the spectrum of MHD turbulence?
6. Do microscopic plasma processes play a role in MHD turbulence such as determining the viscous mechanism or coupling particle energy to the MHD turbulence?

The magnetosphere contains a wide variety of plasma domains including regions sufficiently large to test the ideas of simple MHD turbulence, and the present experimental evidence already supports a turbulence viewpoint. Other regions of the magnetosphere permit increasingly more complex tests such as the addition of boundaries, hot plasmas, finite beta, microscopic processes, and violation of MHD dynamics. Hence the magnetosphere is an attractive environment to study plasma turbulence.

B. Length and Time Scales of Macroturbulence

A thorough investigation of hydromagnetic turbulence requires measurements on all scales ranging from the size of the entire system down to the dominant ion gyroradius, and time scales down to the corresponding ion gyroperiod.

By itself, an Explorer class mission could not provide multipoint observations on the largest interplanetary scales (but could play a role in such studies in conjunction with deep space missions). A somewhat more modest turbulence program would focus on scales small compared with the solar-wind density scale height ($\sim 10^8$ km in the vicinity of earth). The hydromagnetic turbulence scales for the regions of interest are summarized in Table 3-1.

Table 3-1. Hydromagnetic Turbulence Scales

Region	Macroturbulence Length Scales	Macroturbulence Time Scales (Spacecraft Frame)
Solar Wind	100 km to > 10^6 km	0.1 sec to > 1 hr.
Magnetosheath	100 km - 10^5 km	10 sec - 10^3 sec
Magnetosphere	10 m - 10^4 km	10^{-3} sec to > 100 sec

Ideally a PTEM would consist of N spacecraft with separations varying from 10 km to 10^6 km. The lower part of this range (say 50 to 5000 km) would be primarily useful for studies of magnetospheric macroturbulence;

higher separations (say 5 x 10^3 km to 5 x 10^5 km) are appropriate mainly for interplanetary and magnetosheath turbulence. If only a limited range of separations is available, for technical or economic reasons, it may be appropriate to develop a mission primarily focused on either magnetospheric or interplanetary turbulence.

C. Instrumentation

The most essential quantities in turbulence studies are the fluctuating electromagnetic fields and plasma velocities. Ideally, all components of all these quantities would be measured accurately and with high time resolution on each spacecraft in the PTEM array. In practice, this goal is easier to achieve for the fields than for the plasma parameters. An absolute minimum condition for measurements from an N spacecraft array to provide useful information on macroturbulence is a vector magnetometer on each spacecraft of the array. This requirement applies both to interplanetary and magnetospheric turbulence. Required instrumentation is otherwise somewhat different for the two regions, and is summarized below.

Interplanetary and magnetosheath turbulence. The magnetometer should measure the three field components with sufficient dynamic range (~10^{-3} gauss) to avoid saturation in the largest transient interplanetary field; time resolution (current state of art) would be 1-10 Hz. (For microturbulence studies electric field measurements from above the upper range of the magnetometer frequency response to several hundred kHz would be required.) The state of the plasma (density, velocity, etc.) would be determined from plasma analyzers. There is a tradeoff between the sophistication of the plasma analyzer (e.g., being able to measure the full three dimensional velocity distributions of both electrons and ions) and rapid time response. One option would be to have a sophisticated plasma analyzer on each spacecraft, which can intersperse its comprehensive measurements with less comprehensive high time resolution measurements. Another, probably less costly, alternative would be to have a sophisticated analyzer on one spacecraft, and instruments that make only high time resolution measurements of plasma velocity on the others. Higher-energy particle detectors should also be part of the core payload; in this case too, time resolution is the paramount consideration.

Magnetospheric turbulence. In order to study turbulence adequately in magnetospheric convection and in the regions in and near the acceleration zone for auroral electrons, several instrumented spacecraft must probe the region simultaneously. Some of the requisite measurements are listed in Table 3-2. Electric field measurements are emphasized for the components of the velocity perpendicular to B since they can easily be extended to the short wavelengths and high frequencies necessary for studies of microturbulence. High quality magnetic field measurements are vital in order to adequately assess the role of field aligned currents in establishing the acceleration zone and in discharging vorticity through the ionosphere.

Table 3-2. Required Spacecraft Measurements

MEASUREMENT REQUIRED	METHOD	FREQUENCY SCALE*
Vector electric field	Double probes on long wire booms (spherical electrodes necessary for point contact)	1000 Hz
Vector magnetic field	Fluxgate	100 Hz
Scalar density	1. Active method for absolute density	50 Hz
	2. Langmuir probe for fast relative density	1000 Hz
Parallel plasma flow	Drift meter (RPA)	100 Hz

*Microturbulence measurements will require more bandwidth for some of these instruments.

In studies of convection turbulence a variable spacecraft separation of several hundred kilometers is necessary. Vector velocity measurements are necessary at several points in order to determine the vorticity. In the dissipation scale, multiple spacecraft will help determine the wave modes involved and the correlation distances parallel to $\underset{\sim}{B}$.

In electrostatic shock regions the full three dimensional structure must be mapped as instantaneously as possible. The parallel extent is not known but must be reasonably extended due to the relative ease of detection by a polar orbiting satellite. The shock extent is probably quite large parallel to L shells but is only 50-100 km in the meridian. The turbulent region surrounding the acceleration zone is 5-10 times larger.

General. A conscious choice should be made to ensure that the instruments on the N spacecraft are adequate to do the job for which this mission is designed. It is inevitable that the experimentalists will have continued to improve the capability of their instrumentation and will wish to make new types of measurements rather than those which are now customary. However, what is lacking in the study of turbulence thus far is a sufficient number of multipoint measurements, by multiple spacecraft and a strategy to coordinate such measurements in such a way that serious gaps in the characterization of turbulence will not remain after a dedicated mission. The primary objective must be to fill in the missing information in an unambiguous and thorough manner. New science which does not directly serve this purpose must be given second priority. Advances in technology and instrument design (resulting, say, in improved time resolution) could prove valuable; however, state of the art instruments in the above list appear adequate to advance the study of turbulence significantly.

D. Radio Techniques

Spacecraft radio signals can be used to study turbulence or refractive index fluctuations in the solar wind or magnetosphere. As line-of-sight integrated measurements, the radio observations complement the point measurements made directly by spacecraft and are especially useful for global studies. Although various scattering phenomena can be observed the two most useful are (1) phase scintillations and (2) spectral broadening.

Phase scintillations are important for studying the power spectrum of density fluctuations because they contain information on the full range of scale sizes. The most effective way for measuring the phase scintillations is to use a dual-frequency coherent radio system such as the S/X system on the Voyager, Viking and Pioneer Venus spacecraft. For near-earth spacecraft, higher signal-to-noise conditions may exist and measurements in the vicinity of the proton gyroradius in the solar wind (fluctuation frequencies 1 Hz) may be possible. Information on the density spectrum can be deduced from the phase scintillation measurements in a straightforward manner provided that the scintillations are weak (variance of the log-amplitude fluctuations less than unity).

The other scattering phenomenon that is particularly valuable when the scintillations are strong is spectral broadening. For the purposes of studying the density spectrum, spectral broadening observations are similar to intensity scintillations in that they furnish information only on the small-scale flucuations (of the order of the Fresnel size which is approximately 140 km for the solar wind at S-band). Despite this scale size limitation, spectral broadening is an important measurement because the interpretation involves the well-understood second-moment theory.

Solar wind measurements are possible with the spacecraft-to-ground radio link and will depend on the trajectory of the spacecraft. On the other hand measurements of the magnetosphere will have to be carried out using spacecraft-to-spacecraft radio links in order to separate magnetospheric and ionospheric contributions. Also since the electron density is so tenuous in the magnetosphere the frequency of the radio link would have to be lower than S-band.

E. Opportunities for Multipoint Studies of Turbulence Using Data From Existing Spacecraft

At least three missions are providing data which will be used to investigate turbulence and fluctuations in the solar wind: Helios-1 and -2; Voyager-1 and -2; and ISEE-1, -2, and -3. Each of these spacecraft carries a magnetometer which is capable of making measurements of $\underset{\sim}{B}$ with the desired accuracy and time resolution. Each also carries a plasma analyzer which, in certain modes at least, can make high time resolution 3-D measurements of the solar wind protons under most interplanetary conditions. The measurements of density are not as accurate as one would like for studies of compressive fluctuations, and there is room for improvement in the time resolution. Nevertheless, the instruments provide an excellent, high quality data base which can contribute significantly to advancing our knowledge of interplanetary turbulence. All of the spacecraft listed above also carry excellent plasma wave experiments which can provide information on the local plasma turbulence. Perhaps these experiments can also give the very accurate plasma densities that are needed.

Helios, Voyager and ISEE survey a vast region of interplanetary space. Helios-1 and -2 move between 1 AU and 0.3 AU. Voyager-1 and -2 have already made measurements between 1 AU and 5 AU, and they should extend to at least 10 AU. ISEE-3 is in "orbit" about the earth-sun inner libration point. The orbital plane is perpendicular to the earth-sun line, and carries the spacecraft up to within 20 degrees of this line.

The separations between Helios-1 and -2, between Voyager-1 and -2, and among ISEE-1, -2, -3 are suitable for multispacecraft investigations of hydromagnetic turbulence on a variety of scales. The separation between Helios-1 and -2 near perihelion is less than $\approx 10^6$ km, and the separation vector makes a large range of angles with respect to the radial direction and the average magnetic field direction; thus Helios provides an excellent opportunity for the study of fluctuations near 0.3 AU. Farther from the sun, the separation between Helios-1 and -2 increases to a few tenths of an AU, and it is unlikely that one will see correlations between measurements made at the two spacecraft in general. However, there are cases in which the two spacecraft are radially aligned along the nominal spiral direction, and data obtained at these times can be expected to provide useful information about fluctuations. These results are currently being investigated.

Voyager-1 and -2 also provide excellent opportunities for multispacecraft studies of interplanetary fluctuations. Shortly after the launch of Voyager-1, the separation between Voyager-1 and -2 was less than $\approx 10^6$ km. Moreover, the distance betwen Voyager-1 and IMP-7, and -8, (which are in orbit around earth and are often in the solar wind) was also $\lesssim 0.01$ AU for many days. As the Voyagers move away from the sun, their separation increases. For example, the separation was ≈ 0.1 AU at beginning of 1978.

The ISEE spacecraft provide a different but equally promising opportunity to study interplanetary fluctuations. ISEE-3 is always in the solar wind, $\approx 1.46 \times 10^6$ km sunward of the earth near the earth-sun line. ISEE-1 and -2 are in earth-orbit with an apogee of 1.5×10^5 km. Thus, they are in the solar wind during most of each orbit for a few months each year. The distance between ISEE-3 and ISEE-1, -2 is $\approx 1 \times 10^6$ km, which is very favorable for the study of MHD turbulence. The distance between ISEE-1 and -2 is variable, ranging from ≈ 20 km to $\approx 10^4$ km. The smaller separations are appropriate for studies of high frequency turbulence, but one needs separations $\gtrsim 10^4$ km for studies of MHD turbulence. Thus, ISEE-1, -2, and -3 give essentially 2-point observations of MHD turbulence. Of course, ISEE-1 and -2 can contribute much to understanding plasma turbulence in the magnetosheath and magnetosphere.

F. Number of Spacecraft and Their Configuration

A mission aimed at studying turbulence requires simultaneous measurements from N spacecraft, where N is at least 2. The optimum value of N very likely depends on the kind of problem being studied. The experience of meteorology is that even two stations can be extremely effective for separating spatial and temporal variations of <u>certain</u> phenomena, <u>provided that the location of the stations is carefully selected</u>. Generally speaking, N = 3 is far more powerful than N = 2, and N = 4 is even better, if the locations are judiciously selected. The point at which increasing N by one is not desirable is largely determined by economic considerations.

The theory of hydrodynamic turbulence is usually expressed in terms of two-point correlations of the components of the flow velocity; the generalization to hydromagnetic turbulence involves magnetic field components as well, but the emphasis is still on two-point correlations. In the case of the solar wind, a single spacecraft can measure correlations between points aligned along the direction of flow, because the solar wind speed is much larger than the Alfven speed. Additional spacecraft are needed to measure the correlations in the transverse directions. The N spacecraft would have to have variable separation. The time required for major changes in the relative configuration of the spacecraft array is likely to be large in comparison with correlation times. Hence any correlation functions obtained from the data would represent a composite of data swaths widely separated in time.

Clearly any reasonably sized configuration can give valid two-point correlations only if the turbulence spectrum is reproducible from, say, one high-speed stream to the next. Analogous considerations of reproducibility would apply to the determination of magnetospheric turbulence spectra. Whether the necessary reproducibility is present cannot be decided a priori, but important evidence on this point would come from comparisons of the one-dimensional spectra that could be made from available single-spacecraft data

The analog with meteorology emphasizes the importance of judicious orientation of the observing stations; novel suggestions of spacecraft configuration are to be encouraged. One such suggestion is to use tethered pairs of spacecraft, each pair rapidly rotating about its center of mass. By comparing data from the two spacecraft at various time lags, one can sample all separations inside a circle of radius R (= length of tether) in the ecliptic plane. One actually samples a long strip of thickness R because of the super-Alfvenic flow of the wind. One problem of such a scheme is that the rotation period is certainly long compared with the time required for an Alfven wave to cross the distance R, so that the data from two points at a given separation are generally not simultaneous. Hence the correlation function is not measured for scales less than R unless the turbulence is steady over the rotation period.

Let us now consider the optimum number of spacecraft for the study of turbulent fluctuations. If one takes the viewpoint that the primary objective of a PTEM is to obtain two-point correlation functions, the composite nature of the required data set means that there is no major advantage in having three or even four spacecraft rather than two (apart from considerations of the time required to obtain the data set). On the other hand, it is possible to argue that two-point correlations would not give enough information for an adequate understanding of the large-amplitude random fluctuations that occur in space.

As an example, consider the Alfvenic fluctuations found in high-speed solar wind streams. A time series of the components of magnetic field and velocity appears random (see Figure 3-1), and power spectra of these components give a power law (not inconsistent with the Kolmogorov -5/3) over several decades. In these respects the Alfvenic fluctuations appear turbulent. On the other hand, the nearly constant density and, especially, magnetic field strength in such regions are not anticipated on the basis of MHD turbulence. These properties are anticipated for plane Alfven waves. Moreover, the magnetic fluctuations almost always show a clearly defined direction of minimum variance, something that is expected for plane waves but rather surprising for turbulence. Clearly the nature of these regions will not be well understood until we can say unambiguously whether the fluctuations are "waves" or "turbulence," and in particular whether in some sense they are plane waves. This question cannot be answered from two-point correlation alone. It would be strong evidence in favor of the plane-wave hypothesis if the gradient of the components of magnetic field were found always to be parallel to the minimum variance direction, conclusive evidence against this hypothesis if the contrary were found. The required gradient measurement cannot be made with fewer than four spacecraft.

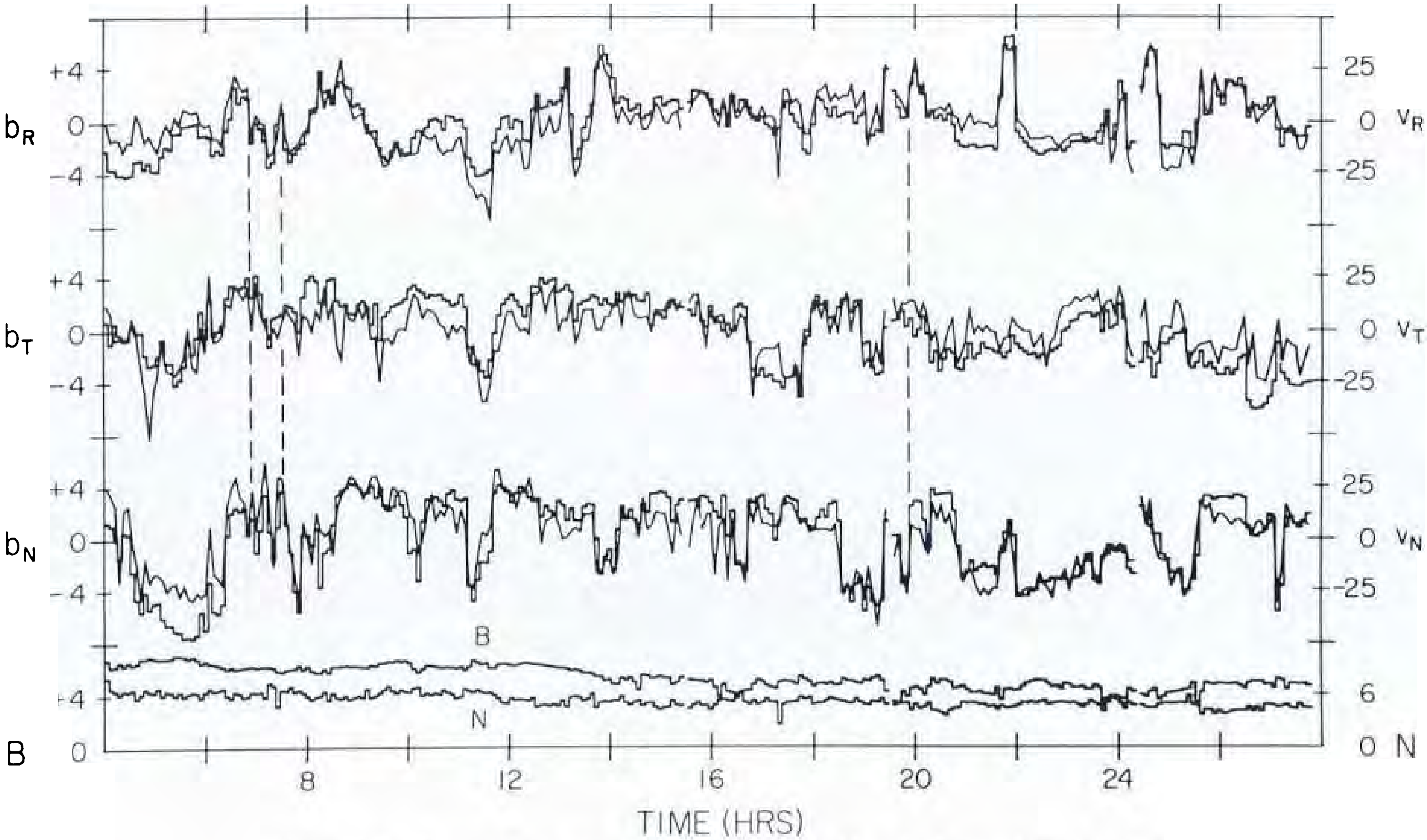

Figure 3-1. Twenty-four hours of magnetic field and plasma data showing nearly pure Alfvenic fluctuations in the solar wind. The upper six curves are 5 min. averages of velocity components (km/sec) and magnetic field components (units of 10^{-5} G). The lower two curves are magnetic field strength and proton number density (Belcher and Davis, 1971).

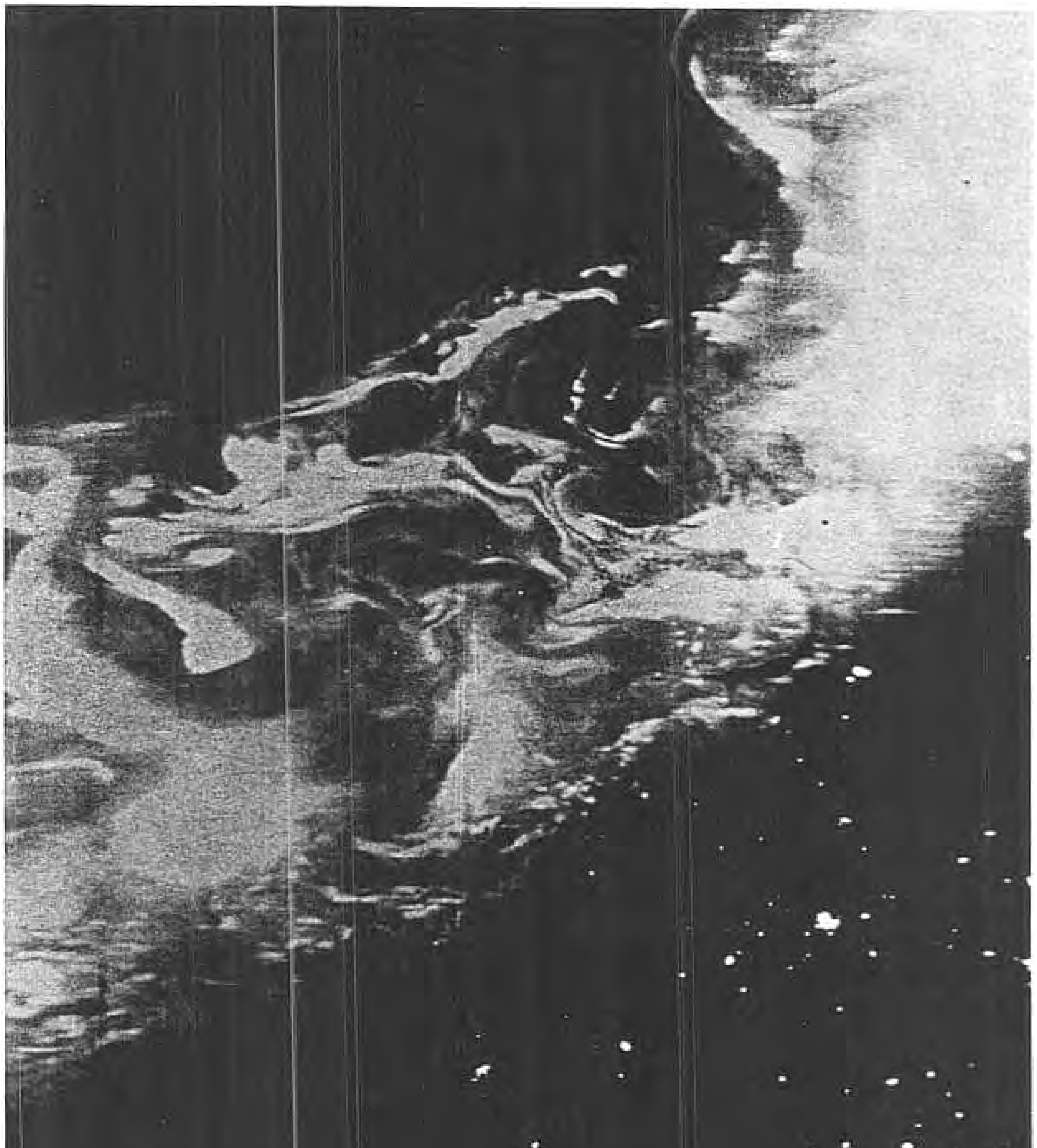

Figure 3-2. Photograph of auroral zone over northern Scandinavia, suggesting two dimensional turbulent flow pattern. Turbulent motion ranges from scale sizes of greater than 1000 km to less than 10 km (resolution of photograph).

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IV. REPORT OF THE MICROTURBULENCE SUBCOMMITTEE

Introduction. Among the various observed microfluctuations, a crucial question in space plasma microturbulence is "Which are strongly and which are weakly turbulent?" A clear answer to this question is necessary to determine whether the large body of weak turbulence theory is appropriate to describe microfluctuations in space plasmas, or whether more difficult strong turbulence theories must be developed to understand such phenomena.

Given the importance of wave-particle interactions in microtheory, the second important question is "What are the macroscopic consequences of microturbulence in space?" It is of particular importance to establish where in space microfluctuations do, in fact, make a significant contribution to macroscopic transport. Microfluctuations are often dismissed as unimportant in the solar wind because the energy density of the fluctuating fields is found primarily at long wavelengths. However, because wave-particle scattering at microwavelengths can be resonant, the strength of the interactions can be orders of magnitude greater than the nonresonant interactions of long wavelength fluctuations, perhaps in some cases compensating for the lack of short wavelength energy density. Also, there exist a variety of well defined structures in space with dimensions of the order of an ion gyroradius; the earth's bow shock is the best known example. Since these structures cannot contain a macroscopic wavelength, their properties must be determined by microfluctuations.

A fully instrumented PTE (see below) would therefore observe not only field fluctuations but also the detailed properties of the plasma particles so that the consequences of the turbulence, e.g., plasma transport, could also be determined. Only with such a full data set can the relative importance of micro- and macro-phenomena be determined.

To choose which among the great variety of space plasma phenomena should be studied, we note that the physical consequences of microturbulence may be present in at least four of the six space plasma problems which the Colgate committee* has identified as important: (1) magnetic field reconnection, (2)

*S. A. Colgate, et al., Space Plasma Physics: The Study of Solar System Plasmas, Vol. 1, Reports of the Study Committee and Advocacy Panels; National Academy of Sciences, Washington, DC, 1978.

acceleration of energetic particles, (3) particle confinement and transport and (4) collisionless shocks. Transport determines the flow of plasma energy from the solar wind, through the magnetosphere and magnetotail to the ionosphere where it couples to the earth's neutral atmosphere. Magnetic field reconnection may occur at the dayside magnetopause, and is likely to take place in the magnetotail during a substorm. Energetic particles are observed at, upstream and downstream of the earth's bow shock, in association with interplanetary shocks and in the magnetotail. If a fully instrumented Plasma Turbulence Explorer would study microturbulence associated with these phenomena, the role of short wavelength fluctuations in space would be much better understood.

A Catalogue of Microphenomena. To define meaningful space plasma experiments in microturbulence, it is necessary to catalogue the observed short wavelength fluctuations and to state some of their properties. Our catalogue of microphenomena is given in Table 4-1. We here draw heavily on papers which have reviewed this subject for the magnetosphere [Shawhan, (1979a)] and solar wind [Gurnett, (1978)], and state only those properties most likely to be of importance to the Plasma Turbulence Explorer study.

We exclude from this list electromagnetic radiation, phenomena such as shocks and solitons which are not subject to a statistical description, fluctuations generated by artificial means such as ionospheric modification experiments, ionospheric plasma modes and fluctuations of relatively small amplitude (i.e., $\delta E < 1$ mV/m and $\delta B < 10^{-2} \gamma$).

In Table 4-1 "w-w" and w-p" refer to fluctuating field energy density wave number spectra S(k) that are predominantly power law (and thus presumably dominated by wave-wave processes) or predominantly peaked (and presumably dominated by wave-particle processes), respectively. Figure 2-3 of the microtheory introduction represents the two type of spectra as they might be observed by a spacecraft. This assumes that Doppler shifts dominate most fluctuation observations and that the observed frequency spectra correspond to wave number spectra in the plasma frame of reference.

Table 4-1. Catalogue of Microphenomena

Region	Observed Fluctuations	Observed Frequency (Name of Possible Wave)	Observed Wavenumber Spectra	Observed Duration	Maximum Field Amplitude	Possible Associated Free Energy	Recent Reference
Auroral field lines (∿400 km)	δE	20-600 Hz	w-p	∿1 sec	1 mV/m	Velocity shear	Kelly & Carlson (1977)
Auroral field lines (> R_E)	$\delta\vec{E} \perp \vec{B}$	0-500 Hz (Ion cyclotron)	w-p	seconds	50 mV/m	$\vec{J} \parallel \vec{B}$, ion beam	Temerin (1978), Kintner et al. (1979)
Auroral field lines (1-many R_E)	δE	10 Hz-10 kHz Peak: 10-50 Hz (Broad band noise)	w-p	∿1 hour	10 mV/m	?	Gurnett & Frank (1977)
Magnetosphere (inside plasmasphere)	$\delta E < \delta B$	10 Hz - 5 kHz (Plasmaspheric hiss)	w-p	continuous	10^{-2} γ	Electron loss cone	Thorne et al. (1979)
Magnetosphere (beyond plasmapause)	$\delta\vec{E} \perp \vec{B}$	$(n+1/2)\Omega_{ce}$, Ω_{uh} (Electron cyclotron, upper hybrid)	w-p	∿5 min.	20 mV/m	$T_{\perp e} > T_{\parallel e}$, Electron loss cone	Kurth et al. (1979)
Magnetosphere (beyond plasmapause)	δB	10-1500 Hz (chorus)	w-p	<1 sec	10^{-1} γ	Energetic electrons, electron loss cone	Tsurutani & Smith (1977)
Magnetopause	$\delta\vec{E}$, $\delta\vec{B}$ $\delta\vec{E} \perp \vec{B}$	5 Hz - 10 kHz (Lower hybrid drift)	w-w	∿1 min.	5 mV/m	$\vec{\nabla} n, \vec{\nabla} T \perp \vec{B}$, $\vec{J} \parallel \vec{B}$, Velocity shear	Gurnett et al. (1979a)
Magnetotail (23-46 R_E)	$\delta\vec{E} \perp \vec{B}$	10 Hz - 40 kHz (Lower hybrid drift)	w-w	∿30 min.	5 mV/m	$\vec{\nabla} B$, anisotropic f_i	Gurnett et al. (1976)
Shocks (Bow and Interplanetary)	$\delta E >> \delta B$	20 Hz - 4 kHz Peak: 200-800 Hz (Ion acoustic)	w-p	Shock width	1 mV/m	Shock	Rodriguez & Gurnett (1975)
Magnetosheath	$\delta E < \delta B$	10 Hz - 70 kHz (Whistler)	w-w	hours	10^{-1} γ	?	Rodriguez (1979), Gurnett et al (1979a)
Magnetosheath	$\delta E < \delta B$	10 Hz - 300 Hz (Lion roar)	w-p	1-5 sec	10^{-1} γ	Proton beam	Smith and Tsurutani (1976)
Solar Wind	$\delta\vec{E} \parallel \vec{B}$	1-5 kHz (Ion acoustic)	w-p	<1 sec	1 mV/m	Ion beam, heat flux	Gurnett et al. (1979b)
Solar wind (upstream of bow shock)	$\delta\vec{E} \parallel \vec{B}$	10-50 kHz (Electron plasma)	w-p	minutes	10 mV/m	Electron beam	Filbert & Kellogg (1979)
Solar wind	$\delta B > \delta E$	1-100 Hz (Whistler)	w-p	1 min.	10^{-1} γ	Electron heat flux	Kennel et. al. (1979)

Relatively long time averages on microfluctuation data tend to produce more isotropic, power law (wave-wave) spectra, while short time averages yield (wave-particle) spectra with relative maxima. This implies that measurements must be fast enough to resolve the most rapid time scale associated with a microphenomenon.

To help choose which regions of space and what kind of fluctuations a Plasma Turbulence Explorer should study, we have set two criteria: 1) the phenomenon should permit study of the fundamental question as to whether the fluctuations are weakly or strongly turbulent and 2) the phenomena should be sufficiently decoupled from other plasma effects to permit a clear study of the consequences of the fluctuations.

Electron Beam Microphenomena. Electron beams and their associated phenomena are a good example of a free energy and associated fluctuations that satisfy criterion 2). Beams propagate along the magnetic field for distances very long compared to the scale size associated with their origin, so that the associated phenomena are independent of any boundary conditions. The high phase speed and frequency of beam-driven electron plasma oscillations puts them in a parameter regime that is clearly distinct from many other plasma modes listed in Table 4-1.

Moreover, electron beam phenomena also satisfy condition 1). The existing data are not sufficient to determine whether, in a given circumstance, the beam-driven fluctuations are weakly or strongly turbulent. However, a great deal of theoretical work has been addressed to this topic and several distinguishing criteria have been proposed, so that the availability of significantly improved data would permit for the first time tests of this fundamental question.

Therefore we propose that a Plasma Microturbulence Explorer should address the topic of electron beams and their associated phenomena.

In recent years substantial progress has been made concerning the origins and effects of electron beams which propagate along geomagnetic field lines in the auroral regions. It is now known, for instance, that such beams are responsible for auroral kilometric radiation. The detection of this radiation can be considered a remote sensing of turbulent plasma processes associated with electron beams. Recent high time resolution data from ISEE show that the auroral kilometric radiation has a discrete, narrow band structure in frequency and time. This implies a small spatial scale region for the generation of the individual bursts. Previous investigations had already located the overall region of generation on auroral field lines between a few thousand and 20,000 km above the earth. Thus this is one example of a plasma process that is ready for in situ investigation with instruments capable of high temporal and spatial resolution. It is ready for detailed investigation because we know where the process occurs and we know what some of its consequences are but due in part to a lack of in situ measurements in the generation region there is no adequate explanation of the process.

There are several other examples of phenomena associated with auroral electron beams. Recent investigations have found regions of space on auroral field lines where there is an electric field parallel to the magnetic field; electron beams are also found in these regions. There may be a complex interaction between the two phenomena in that the parallel fields in part produce the electron beam which, in turn, produces plasma microturbulence which sustains the electric field. Understanding plasma microturbulence is thus important for understanding processes that produce electron beams. The complex interactions in these regions also produce VLF hiss, upper hybrid waves, lower hybrid waves and electrostatic shocks. The parallel fields associated with the electron beams also produce ion beams which propagate in the opposite direction and which, in turn, are associated with electrostatic ion cyclotron turbulence. These processes have been identified and their location is known. Thus they too are ready for detailed study of the basic plasma physics involved.

It should be pointed out that the region of auroral beams is also the region of low frequency guiding center turbulence mentioned elsewhere in this report. Thus a satellite equipped to study the microturbulence associated with auroral beams would also be useful for the study of short wavelength aspects of guiding center turbulence.

A second region of space where electron beam associated phenomena have been observed is in the solar wind upstream of the earth's bow shock (Filbert and Kellogg, 1979). Here electrostatic field noise near the plasma frequency has been correlated with connection of the associated magnetic field lines to the earth's bow shock. In addition, electromagnetic radiation at the plasma frequency and its first harmonic have been observed in the upstream region. Although no unstable electron distribution functions have been observed, there is good indirect evidence that both the plasma fluctuations and the electromagnetic radiation are generated by the electron beam instability. An important role of a Plasma Turbulence Explorer would be to study electron distributions with a speed and accuracy greater than any existing mission in order to determine whether unstable distributions are in fact present.

Measurements: Existing Missions. Many of the recent measurements of electric and magnetic fluctuations at microturbulence frequencies (> 1 Hz) have been reviewed by Shawhan (1979b).

Present state-of-the-art is represented by the ISEE-1 and -2 spacecraft which are exploring the near earth solar wind and outer magnetosphere. The various experiments carried on these vehicles are described in a special issue of IEEE Transactions on Geoscience Electronics, GE-16, #3, July 1978. Both vehicles carry magnetometers to measure slowly varying magnetic fields, antennas to study slowly varying electric macrofields and fluctuating electric and magnetic microfields, and fast plasma experiments capable of obtaining 2D ion and electron distribution functions in three seconds and full 3D velocity distributions in 24 seconds. In addition, a full complement of energetic electron, proton and ion detectors are on board. Both vehicles have orbit adjustment capabilities so that they remain relatively close together in their flight.

These capabilities permit use of the ISEE pair to study not only correlations between fluctuations and plasma distributions, but also correlations between fluctuations observed at two points in space. Such studies have not yet been reported in the literature. What has been reported concerning electron plasma frequency fluctuations from existing missions may be summarized as follows:

Intense narrow-band electrostatic fluctuations near the electron plasma frequency are occasionally detected in the solar wind by the Helios, Voyager and ISEE spacecraft (Gurnett, 1978). Polarization measurements with Helios show that the electric field of these waves is parallel to the static magnetic field, which together with the oscillation frequency uniquely identifies these as electron plasma waves. These waves usually occur in association with solar flares and type III radio bursts; when they do, they are often very intense and show a clear tendency for saturation (Gurnett, Anderson and Tokar, 1979) near $\delta E^2/8\pi n k_B T \simeq 10^{-5}$. Studies of numerous events at various radial distances from the sun show a systematic decrease in the saturation field strength with increasing radial distance.

A very large ratio of peak-to-average field strengths, $\sim 10^3$, is observed for these fluctuations, indicating that they consist of many, short, very intense bursts, with a relatively long dead time between bursts. The observation of such spiky bursts has stimulated a substantial body of plasma microtheory concerning the possible development of Langmuir solitons. Competing theories describe the bursts as due to stable (Papadopoulos and Freund, 1978) and unstable (Goldman et al., 1980) solitons, and the conversion of electrostatic plasma fluctuations to electromagnetic radiation as due to coherent (Smith, et al., 1979 and Goldstein, et al., 1979) and incoherent (Smith, 1977) processes.

The time resolution of present solar wind plasma wave instruments (e.g., 50 msec on Helios) is insufficient to resolve the detailed structure of this turbulence. Thus a Plasma Turbulence Explorer bearing a very fast plasma wave analyzer would provide important new data in an area where there has already been substantial interplay between theory and observation.

Measurements: Other Proposed Missions. The Dynamics Explorer, to be launched in the early 1980s, will use two satellites in coplanar polar orbits at different altitudes to study the physical mechanisms coupling the magnetosphere, the ionosphere and the atmosphere. Only the high altitude vehicle will carry instruments capable of studying microturbulence. Although it will also carry a plasma analyzer and will study wave-particle effects in the auroral field line regions, it will provide only single point fluctuation measurements.

An important near-earth NASA mission for the mid-1980s, OPEN, is planned to involve four spacecraft (Origin of Plasmas in the earth's Neighborhood; Final Report of the Science Definition Working Group, NASA, April 1979). However, as described by this document, the primary OPEN mission is to study plasma and plasma energy flow with special emphasis on plasma composition and charge state observations. Although four spacecraft with fluctuation instrumentation will be involved in OPEN, they will pass close enough to one another to study microscale correlations only during extremely improbable encounters.

Measurements: Plasma Turbulence Explorer. Fundamental to the Plasma Turbulence Explorer is the concept of multi-point observations; the simultaneous measurement of field or plasma parameters at several nearby points in space. This concept implies the use of multiple probes or spacecraft kept relatively near to one another. Such capability will yield information about both the wave number and frequency dependence of the fluctuation correlation functions which have not been provided by any other existing or planned mission.

Here we will address the differences between missions to study macroturbulence and microturbulence in general, and then address specific properties of an electron beam microturbulence mission in Section V.

1) The scale lengths of microturbulence are considerably smaller than those of macroturbulence, and therefore require considerably closer separation of the spacecraft. Wavelengths of various microinstabilities range from the ion gyroradius down to the electron Debye length or the electron gyroradius, whichever is shorter. These scale lengths as a function of distance along a field line above the earth are indicated in Figure 1.

This figure shows that at altitudes $\lesssim 10^4$ km the full range of microturbulence wavelengths can be spanned by several spacecraft separated by distances of order 1 km. Closer to the earth, the microturbulence scale lengths are short enough that the turbulence might be studied from only one suitably instrumented spacecraft (say with variable length booms).

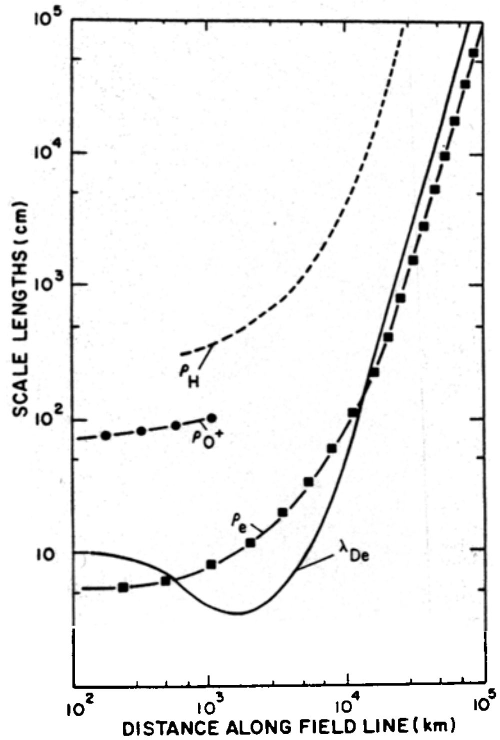

Figure 4-1. The ion cyclotron radius ρ_i, the electron cyclotron radius ρ_e, and the electron Debye length λ_{De} as functions of distance along a field line above the earth.

2) Whereas macroturbulence is characterized by fields and a limited number of space-and-time dependent plasma variables such as density and flow velocity, microturbulence involves detailed interactions between the fields and the velocity distribution functions of the plasma. Thus any mission to study microturbulence should carry plasma analyzers capable of accurately observing electron and ion distributions at rates commensurate with those of the microturbulence processes under study.

The goal of the field diagnostics would be to measure not only the frequencies and amplitudes of the microturbulence, but to provide data to compute field-field correlation functions as functions of time and relative spacecraft separation. If it would be possible to extract both frequency and wave number information from these correlation functions, one could determine whether several of the fundamental assumptions of weak turbulence theory discussed in the introduction (the existence of well defined modes $\omega(\vec{k})$ and broadly resonant driving species) are valid.

Radiowave scintillation observations would study electron density fluctuations. The basic experiment would be to transmit a monochromatic radio signal from one of the spacecraft. As the wave propagates through the turbulent plasma, the phase of the wave is distorted by electron density irregularities along the line-of-sight. (In the geometrical optics limit the phase perturbation is directly proportional to the integrated density perturbation.) Amplitude fluctuations develop as the wave propagates, caused by random constructive and destructive interference from the spatial distribution of phase irregularities in the transmitted wavefront. The receiver would be on the other spacecraft and would estimate amplitude and phase as functions of time. The goal of the experiment would be to estimate statistics of the density fluctuations from the received signal statistics.

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V. TECHNICAL AND ENGINEERING CONSIDERATIONS ASSOCIATED WITH A PLASMA TURBULENCE EXPLORER MISSION

A. Scientific Requirements of the Macroturbulence Mission

The following is a discussion of the principal scientific requirements associated with a mission to study hydromagnetic turbulence in the solar wind. The purpose of enunciating these requirements is to enable advanced planning personnel to carry out a preliminary design of such a mission. At the time when these requirements were generated, no mission had been designed and an attempt was made to state the requirements in general terms without trying to dictate the design.

The parameters to be measured are the vector magnetic field and the solar wind plasma. The instruments to be carried on board the spacecraft are a magnetometer and a plasma analyzer capable of measuring both ions and electrons. The measurements are to be made near 1 AU and may be made near earth so long as they are not contaminated by the interaction of the solar wind with the terrestrial magnetosphere.

The major objective is to obtain correlation functions and wave number frequency spectra or their equivalent. The wavelength range of interest extends from 10^2 to 10^7 km. The wave periods of interest range between 1 sec and 10 hours.

The solar wind is known to consist of several different types of regions such as fast corotating streams, flare-generated plasma and rarefaction regions. It is important to identify the type of solar wind in which the high resolution measurements above are acquired. It therefore becomes necessary to acquire magnetic field and plasma data continuously over a longer interval of 10 days surrounding the high resolution data but at lower time resolution. Field and plasma measurements over intervals of one minute are acceptable.

The spacecraft spin axis should be perpendicular to the ecliptic in order to facilitate the plasma measurements by automatically providing a scan in azimuth. In order to achieve high time resolution, the spacecraft spin rate should approximate one revolution per second. The instantaneous spacecraft attitude, determined by the spin axis orientation and the roll angle with respect to the sun-spacecraft direction, must be known to better than 1°.

The telemetry rates associated with the instrument are estimated as follows. Each field vector corresponds to 30 bits. At a sampling rate of 10 samples/sec (which provides a time resolution in excess of 1 sec), the magnetometer bit rate is 300 b/s. Assuming the solar wind measurements consist of currents measured to 10 bits at 30 energy or voltage levels, 10 azimuth and 10 polar angles, the bit rate becomes 3×10^4 b/s. It will probably not be necessary to make 3 dimensional measurements of the distribution function continuously. Consideration should be given to obtaining less comprehensive information, e.g., by determining the moments of the distribution function in-flight or by using circuits that track the peak of the distribution.

The low resolution plasma and field data can be acquired at a bit rate as low as 1 kb/s. For example, 3×10^4 bits/10^3 b/s = 30 sec resolution or one minute resolution for measurements of both ions and electrons. The low resolution magnetic field measurements require a proportionately smaller bit rate, e.g., 30 bits/3 sec = 10 b/s.

The estimated total mass of the magnetometer and plasma analyzer is 15 ± 5 kg and the total power is 15 ± 5 watts.

The spacecraft separation distances are required to change from a minimum of 10^2 km to a maximum of 10^7 km. If this requirement proves too difficult to achieve, acceptable results could be obtained for separations ranging from 10^3 to 10^6 km in order to test for possible time variations. This distance range should be traversed several times. In order to achieve the maximum separation in a reasonable time interval, e.g., 1 year, a separation speed of 10^{7+3}m/3×10^7 sec = 300 m/s is required.

The directions in which the spacecraft are separated are also important. Consider a cartesian coordinate system based on the direction to the sun (S) and to the north ecliptic pole (E), i.e., let the X-axis coincide with S, the Z-axis with E and define the 3rd orthogonal axis: Y = E x S. Let the origin of these coordinates coincide with one of the spacecraft. Separation vectors can then be drawn from the origin to the other points of observation, i.e., the other spacecraft. The distribution of these vectors should be reasonably isotropic, i.e., essentially covering all azimuth and elevation angles.

B. Plasma Microturbulence Explorer Requirements

The goals of the mission are to study energetic electron beams and associated microphenomena in near earth space. The enhanced plasma frequency fluctuations which are the signatures of these beams are observed in the solar wind upstream of the earth's bow shock primarily in the dawnside sector, and energetic electrons themselves are frequently observed along low altitude auroral field lines. Thus the mission suggested by this committee should cover both of these regions, spending as much time as possible in the areas of interest. The suggested perigee and apogee are 3000 km and 15 earth radii, respectively.

We propose that the mission consist of two spacecraft separated by a tether. The wavelengths of the electron beam instability are 200 Debye < 6 km for altitudes of less than 2×10^4 km in the auroral zone (see Figure 1 of Section IV) and in the upstream solar wind; the wavelengths of the associated solar wind ion acoustic turbulence will be somewhat less than this. To measure the associated fluctuations efficiently, we propose a tether 10 km in length with probes to measure electric potential differences spaced along the tether at intervals of 1 m, 10 m, 100 m, 1 km and 10 km. Two more conventional antennas (100 m in length, orthogonal to the tether and to each other) should be mounted on each spacecraft to provide information about polarization and other properties of the relatively short wavelength fluctuations.

The associated instrumentation should analyze the frequency range from as low frequencies as possible to 200 kHz; of particular importance is the range about the electron plasma frequency which is typically 25 kHz in the upstream solar wind. The instrumentation should be able to study fluctuating electric fields in the range of 1 μV/m to 100 mV/m.

The array of sensors represents a plasma wave interferometer which is capable of detecting wave lengths from 1 m to roughly 100 km. The measurement of wave lengths is necessary to determine both the phase velocity and dispersion relation of the modes associated with the electron beam turbulence. Such an interferometer has never flown before and is a significant improvement over any existing space plasma wave measurements.

The associated magnetic fields should be measured by conventional methods; vector DC, search coil and loop magnetometers spanning the frequency range from DC to 100 kHz would be appropriate on each spacecraft.

The electron and ion distribution functions should be studied by plasma analyzers. The electron analyzers should span the range from thermal to about 30 keV energies, should yield a three dimensional velocity space measurement, and should be as fast as technology will allow - a one second time resolution would be desirable. The best situation would be to have identical instruments on each spacecraft.

The ion analyzers are less critical; it would be desirable to have the same energy range with three dimensional capability, but a slower measurement time of the order of 10 seconds could be tolerated. Having a second ion instrument is much less important than for the electrons, because the proposed mission will concentrate on electron dynamics.

Supplementary diagnostics to directly measure density fluctuations should include a Langmuir probe and a radio wave experiment, and an active experiment to measure plasma density would also be appropriate.

The data should be gathered in two modes: a slow mode for obtaining distributions and fields once per minute over most of the mission orbit when no electron beams are likely to be present and a fast mode for gathering data at the fastest possible rate for the relatively infrequent conditions such that energetic electrons are present. Some kind of "trigger" criterion should be set so that the fast rate would automatically turn on when beam-associated phenomena are encountered, whenever they happen to arise along the orbit. Along with a trigger a mass storage device such as a magnetic bubble memory would be used to obtain data just before the triggering event and to store the data from the triggering event for somewhat slower transmission to earth.

C. Magnetospheric Turbulence Explorer (MTE) Requirements

Electrostatic guiding-center turbulence in the magnetosphere occurs primarily outside the plasmasphere and is most intense in the auroral zone where it is found on almost a continuous basis. Preliminary evidence suggests that the turbulence occurs at all altitudes. The MTE mission would be conducted by polar orbiting spacecraft penetrating auroral magnetic field lines between .1 and 3 R_e. Since electric field instrumentation works best at lower altitudes in higher density plasmas, the mission should start with apogee near 3 R_e and move downward in altitude.

Diagnostic instrumentation should include plasma velocity measurements to sense fluctuation scale lengths from the ion gyroradius ($\simeq$10m) to the width of the auroral oval ($\simeq$1000 km). This measurement is best performed with double probe electric field meters operating in the frequency range of DC to 1000 Hz. Since the spectrum is expected to be a power law, a resolution of 1mV/m is adequate in the DC regime while 1μV/m is adequate in the AC regime. The exact degree of two dimensionality in the turbulence should be tested by performing vector measurements. To calculate velocities from electric fields, a magnetic field instrument will also be needed. Since field-aligned current structures may act as carriers of viscosity, the magnetic field measurement should be conducted from DC to 1000 Hz. Two magnetometers, a vector helium magnetometer (DC) and a search coil, may be necessary to cover this frequency range. The DC magnetometer can resolve 10 mγ while the search coil resolution should resolve 1 milligamma, with the sensitivity crossover at approximately 1 Hz.

To calculate the covariance spectra through correlations the electric field measurements should be conducted at a variety of separations extending from the ion gyroradius to the width of the auroral oval. At short distances (1 to 100m) the crosscorrelation functions can be generated from paired colinear double probes on one spacecraft with telescoping booms. Correlation functions for larger separations will need at least two spacecraft whose separation distances gradually vary from 100m to 1000 km.

The telemetry rates are given by considering 6 AC measurements at a Nyquist frequency of 1000 Hz with 12 bit resolution or 144 kbit/s. The telemetry should be operated continuously when the spacecraft is in the auroral zone.

VI. RECOMMENDATIONS

Some form of plasma turbulence is present in virtually all geophysical and astrophysical situations, and it plays a central dynamical role in many of them. It is also present and important in a large fraction of laboratory confinement (fusion) experiments. A systematic investigation of phenomena associated with plasma turbulence is overdue. We recommend that NASA undertake such a systematic investigation and suggest three possible missions ranked in order of priority.

(1) Macroturbulence in the Solar Wind. Of the various conceptual frameworks in which plasma turbulence theory has been addressed, magneto-hydrodynamic (MHD) theory is the most mature, the most nearly complete, the simplest, and requires the least elaborate instrumentation to test. Such diverse phenomena as those in the solar wind, the solar corona, and quasi-stellar radio sources (to name but a few examples) are all involved with MHD turbulence in a fundamental way. Solar-wind MHD turbulence, of those kinds directly accessible to us, is the farthest from boundaries and the most likely candidate to exhibit the high degrees of symmetry (see Section II) desirable for a simple theoretical description.

A realistic experimental goal of such a solar wind macroturbulence mission would be the measurement of two-point covariances and correlation functions for the magnetic field and velocity field in a coordinate frame in which the local mean velocity field is zero. These should be accumulated as functions of the spatial separation $\underset{\sim}{r}$, the temporal separation τ, and the angle θ between $\underset{\sim}{r}$ and the mean local magnetic field $\langle \underset{\sim}{B}_o \rangle$, Rather large intervals of r and τ may be required to get beyond the correlation times and distances. These long intervals may put stringent requirements on the orbital dynamics required to sample the space adequately. To assess the limitations imposed by these requirements involves going beyond the preliminary considerations given in Section V. At least two spacecraft with highly variable separations are required and quite possibly larger numbers would be desirable; but detailed answers to this question require cost assessments that have not been done. For preliminary estimates of the technical requirements of a macroturbulence mission in the solar wind, see Section V-A.

(2) Microturbulence in the Magnetosphere and Solar Wind. Plasma turbulence in the Vlasov equation framework predicts a wealth of physical effects that are averaged out or glossed over in MHD. Selected regions of the single-particle phase space are identified as being particularly efficient at the exchange of energy between the electromagnetic fields and the particle motions: a class of phenomena usually called "wave-particle interaction". These effects, most tractable at length scales less than an ion gyroradius, present a wide variety of dynamical behavior unknown to MHD, and likewise are to be expected in virtually all solar-terrestrial plasmas except strictly collision-dominated ones. Because the particle distribution functions are involved on the same footing as the electromagnetic fields, the relevant numbers of phase space variables increase considerably, and a more sophisticated mathematics is required to discuss such phenomena as the transfer of excitations among spatial scales. Particle detectors capable of measuring three-dimensional velocity space distributions with the same temporal resolutions as in the measurements of the electromagnetic fields are required. Because Vlasov turbulence is so general and so various, a longer-term and more strenuous effort will be required to apprehend it. For preliminary considerations of some of the technical requirements of a Vlasov turbulence mission, see Section V-B.

(3) Electrostatic Guiding Center Turbulence in the Magnetosphere. On auroral field lines, a case can be made that the dominant plasma motion is self-consistent electrostatic drift transverse to the magnetic field lines. The mathematics for this two-dimensional drift approximation is simple and closely related to the two-dimensional hydrodynamics of Navier-Stokes flow. A relatively complete diagnosis is provided by pointwise measurements of electrostatic fields and potentials. Except for the relatively limited applicability of the model (two-dimensional, guiding-center, electrostatic plasma), the simplicity of this mission would make it the logical one to do first. For preliminary consideration of some of the scientific requirements of a magnetospheric drift turbulence mission, see Section V-C.

In addition to the three above recommended missions, it should also be urged that NASA promote, in parallel, the development of a more complete theoretical structure than now exists to accommodate the data when they begin to arrive. Such advances as have occurred in MHD turbulence theory have mostly taken place under assumptions of higher degrees of symmetry (see Section II) than apply to perhaps any naturally-occurring case. The development of a systematic structure for Vlasov theory (from which such concepts as spectral transfer have often been entirely excluded) should also be encouraged. The broad applicability of microturbulence to such diverse situations as beam-plasma interactions in solar-wind streams and radiation from pulsars and Jupiter, means that an understanding of Vlasov turbulence is a necessary ingredient of any ultimately satisfactory understanding of these phenomena.

The necessary theoretical advances needed to develop such structures will require sustained, intense effort, and substantial numerical support in the form of computation and simulation of the effects. A model for the satisfactory interaction of theory, experiment, and computation might be the one now in operation at the National Center for Atmospheric Research in Boulder, Colorado.

A final recommendation, given a lesser but not a zero priority by the panel, is that NASA might want at some time to consider the building of a space plasma laboratory in support of space exploration of such plasma phenomena as turbulence. Even though the terrestrial investigation of space plasma effects is bound to be less satisfactory in some respects than the "real thing", the relative economy of relying on re-usable laboratory equipment makes the possibility attractive.