Part III

Panel Discussion and Symposium Summary

Section A

Panel Discussion on Common Physical Processes and Mechanisms for High-Energy Emission from Astrophysical Plasmas

Highly Energetic Physical Processes and
Mechanisms for Emission from Astrophysical Plasmas
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Solar Flares, the Solar Corona, and Solar Physics

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Abstract. The Sun serves as the local physics laboratory for studying the suprathermal activity phenomena of stars. Scrutiny of the Sun has led to the discovery of a host of previously unknown physical effects, largely within the classical physics of Newton and Maxwell, but including quantum mechanics and lepton physics as well.

Every new observational window into the astronomical universe has opened a new vista of exotic objects of vigorous activity, ranging from pulsars to quasars to gamma ray bursters, etc. These dynamical objects are powered by:

1. Gravitational infall (accretion disks, supernovae).
2. Rotation (Jupiter, pulsars, galactic radio jets, etc.).
3. Radiation pressure (massive stars, supernova shells).
4. Thermal convection (Sun and other late-type stars).

When we examine the closest active object—the Sun—we discover a whole new world of small-scale effects underlying the activity. The "microscopic" examination of the Sun does for astrophysics what the microscope has done for biology, showing the small-scale dynamics responsible for the overall macroscopic activity.

Thus, we learn from the Sun, and project into the distant astronomical objects, that the activity begins with fluid motions in which magnetic fields have become "hopelessly" entangled. It is the fundamental properties of the magnetic fields that create the observed universal suprathermal effects, in ways that we could never have imagined and which we still do not fully understand. The ultimate goal of solar physics is, of course, to show how a stable, self-gravitating object like the Sun is compelled by the basic laws of physics to produce such dynamical phenomena as the sunspot, the million degree corona, hundred million degree flares, fibril magnetic fields, the coronal mass ejection, the cyclic generation of a general magnetic field, etc. In a very general way, we can say that the extreme suprathermal aspects of the Sun are a consequence of rapid magnetic reconnection across the tangential discontinuities (intense current sheets) created by the Maxwell stresses. That is to say, in almost all field topologies (i.e. all but the very simple symmetrical topologies that we use in theoretical calculations), the relaxation to static equilibrium necessarily creates surfaces of tangential discontinuity within the field as a consequence of the nature of the

Maxwell stress tensor. Where the field is not allowed to relax to static equilibrium, the convective motions commonly drive lobes of field together with the same effect.

It is an interesting exercise to list some of the more exotic magnetic and suprathermal phenomena exhibited by the Sun, recalling again that none of them could have been anticipated on theoretical grounds alone, and most are still only partially understood, if at all.

1. Cyclically appearing dark spots with magnetic fields of 2–3 kilogauss, surrounded by light and dark penumbral filaments of horizontal and steeply inclined magnetic field, respectively, and containing umbral bright points and light bridges.
2. Bipolar magnetic active regions of 10^2 gauss in which the dark spots appear.
3. Cyclic polar dipole magnetic field (10 gauss).
4. Fibril structure of the photospheric fields, with widely spaced fibrils of 1.5 kilogauss and 10^2 km diameters.
5. Prominences.
6. Coronal mass ejections.
7. Chromosphere.
8. Faculae and plages, where the mean field exceeds about 30 gauss.
9. Hypoactivity during the 15th and 17th centuries, and hyperactivity during the 12th century.
10. Variations in total brightness by 0.15 percent with the 11-year magnetic activity cycle, and by something of the order of 0.5 percent during the centuries of extreme behavior.
11. Flares, from the limit of detection ($\sim 10^{25}$ ergs) up to the largest at 10^{32}–10^{33} ergs.
12. Magnetically open coronal holes and the fast solar wind (500–800 km/sec).
13. Diffuse X-ray corona and the slow, dense solar wind (250–400 km/sec).
14. X-ray coronal loops in the bipolar magnetic regions.
15. Solar acoustic p-modes, providing the science of helioseismology.
16. The peculiar internal rotation profile $\Omega(r,\theta)$ deduced from helioseismology.
17. The greatly-reduced thermonuclear neutrino emission detected at Earth.

All of these had to be seen to be believed, and seeing them was possible only because of the proximity of the Sun.

The observational discovery of these phenomena stimulated theoretical research, leading to the discovery or recognition of hitherto unknown physical effects and principles residing in the equations of Newton and Maxwell, thermodynamics, and statistical mechanics. Prominent among these new concepts were:

1. Magnetohydrodynamics (MHD) describing the dynamical behavior of magnetic fields in fluids unable to support a significant electric field in their own moving frame of reference. From the basic concepts of MHD, there followed the concept of ...
2. Magnetic buoyancy.
3. Field generation by some form of α-ω dynamo process.
4. The essential concept of turbulent diffusion of magnetic fields and the realization of its *inapplicability* to the relatively strong mean fields in the Sun.
5. Dynamical rapid reconnection of magnetic fields.
6. Spontaneous creation of surfaces of tangential discontinuity (i.e. current sheets) by the topology of the magnetic field.

Outside MHD, some of the concepts (that spring immediately to mind) were:

7. Thermal instability.
8. Non-LTE, in which eclipse spectra of the chromosphere played a leading role in showing the inapplicability of Local Thermodynamic Equilibrium (LTE).
9. Ongoing expansion of the outer regions of the strongly bound solar corona to produce the supersonic solar wind at large distances from the Sun.
10. Solar acoustic p-modes.
11. Compact and high-speed downdrafts in the strongly stratified convective zone.
12. Applications of the negative hydrogen ion.
13. Neutrino oscillations.

It must not be thought that these principles, gleaned thus far from basic theoretical principles, exhaust the repertoire, for it is clear that they offer only partial explanations here and there among the active phenomena of the Sun. There is still no explanation for the solar compulsion to form sunspots, let alone the complicated structure of the penumbra. Nor is it clear what causes the facula and plage phenomenon. As already noted, the flare is evidently an explosive magnetic reconnection process, beginning at a single strong, tangential discontinuity, followed by a sea of small bursts of rapid reconnection throughout the regions of field on either side of the principal discontinuity. Such events range downward to the individual observable microflares of 10^{25}–10^{26} ergs, and theory suggests that they occur down to 10^{22} ergs or smaller (nanoflares). The reconnection process is itself a complex dynamical phenomenon, admitting of many different forms that depend critically on the initial conditions and the boundary conditions used in the calculation, even without the additional complexity of plasma turbulence and anomalous resistivity generated in the intense current sheet. It appears that the coronal hole and the associated high-speed solar wind may be heated primarily by microflares among the magnetic fibrils and ephemeral active regions. It also appears that the intense X-ray loops in the bipolar magnetic regions may be heated primarily by the nanoflares arising in the spontaneous tangential discontinuities created by the continual convective shuffling of the photospheric footpoints of the bipolar field.

It appears that the cyclic general magnetic field of the Sun, whose azimuthal component provides the bipolar active regions and the sunspots, is generated by an α-ω dynamo operating in the vicinity of the bottom of the convective zone. However, it is not clear why the small-scale ephemeral, bipolar active regions and the magnetic flux bundles surfacing in the supergranules have a statistical behavior different from the 11-year cycle of the general bipolar active regions. Nor is it clear why the magnetic fields are everywhere in such an intensely fibril state, with indirect evidence that the fibrils are much more intense (50 kilogauss or more) deep in the convective zone than the 1.5 kilogauss exhibited at the surface. Perhaps the most serious theoretical difficulty is the absence of any idea how the essential diffusion and dissipation of the general field occurs. The successful operation of the α-ω dynamo requires substantial diffusion in order that the process be irreversible. The traditional concept of turbulent diffusion of a vector field is based on analogy with the well-known and thoroughly tested turbulent diffusion of a scalar field, e.g. smoke, whereas the kilogauss mean azimuthal field inferred to exist at the bottom of the convective zone is much too strong to submit to the enormous stretching and intensification indicated by the analogy. It may be that the individual fibril, rather than the mean field, is the basic magnetic entity, but so little is known about the lives and interactions of the unresolved individual fibrils that nothing more can be said with assurance.

This brings us to the fact that scientific investigation of the active features of the Sun is both led and limited by observation. The observations have progressed far enough to show that the crucial features of much of the activity are on scales of 10^2 km or less, far below the ability of existing telescopes to resolve. The facula, the plage, the fine structure of a sunspot, the individual magnetic fibrils, the interactions between fibrils, the microstructure of flaring fields, etc. simply cannot be studied with the presently available angular resolution of $0.5''$(400 km) or worse imposed by the atmosphere above the telescope. The occasional momentary glimpses at $0.3''$(200 km) are tantalizing but insufficient. Space observations in UV and X-rays are progressing nicely, and it is essential to bring ground-based observational facilities up to the present state of the art. That means adaptive optics providing resolution of $0.1''$(75 km) or better in visible light for substantial periods of time, supplemented with infrared capability to perhaps 15μ (to exploit the Zeeman sensitivity and IR LTE to their fullest). At the same time, the need is for high dispersion spectroscopy at rapid cadence (10 sec) to follow the rapidly varying micro-scale dynamics. A simple calculation shows that this requires large (4 m) areas for photon collection. Such an Advanced Solar Telescope is essential if we are to attack the scientific frontier presented by the Sun. It is only from a proper understanding of the suprathermal dynamics of the Sun that we can hope one day to judge to what degree we understand the suprathermal dynamics of the unresolved, distant active objects.