Section B

Symposium Summary

Highly Energetic Physical Processes and
Mechanisms for Emission from Astrophysical Plasmas
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Symposium Summary and Concluding Remarks

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Abstract. The symposium included invited papers, a panel discussion, and poster papers. In the following, I have summarized what to me were some of the more interesting parts of invited papers under the headings of trends, particle acceleration and heating, disks and jets, gamma-ray bursts, and other sources.

Trends

In this symposium, "high energy" referred to thermal emission from plasmas between 10^6 K and 10^9 K, nonthermal emission of photons up to 1 GeV, and cosmic rays up to 10^{11} GeV.

Thermal emission, either blackbody or thermal bremsstrahlung, can be identified by the exponential cutoff for photon energies about k_BT. Spectral features such as ionization edges and lines can be used to determine temperatures up to about 10^8 K; however, above that temperature, all of the abundant elements are completely ionized. Electron densities in the range 10^8 cm^{-3} to 10^{14} cm^{-3} can be determined. The *Chandra* X-ray observatory, whose launch was unfortunately delayed until after the symposium, promises to carry out spectroscopy of a wide range of energetic sources, including thermal emission by neutron stars (at whose surfaces general relativity predicts a gravitational redshift of 2.7) and emission by hot gas in clusters of galaxies, where the cosmological redshift of the iron Kα line can be determined. An avalanche of data is predicted.

Nonthermal emission, such as synchrotron emission and inverse Compton scattering, can be identified as such from power-law behavior and breaks in the spectrum. Polarization, a key diagnostic of synchrotron radiation in the radio band, is difficult to measure in the X-ray band. Unfortunately, diagnostics for nonthermal radiation comparable in power to the spectral features characteristic of thermal radiation seem to be lacking.

Although the Sun is comparatively faint in absolute terms in the high energy bands ($\sim 10^{27}$ erg s^{-1}), it has been possible to study it in great detail in those bands because it is so close. As in the case of most other stars in the H-R diagram, the emission is highly correlated with magnetic activity, as, for example, when bursts of energetic radiation are emitted when magnetic reconnection occurs in magnetically complex regions. Solar physics, which has long dealt with large amounts of data, offers many lessons for high-energy astrophysics, including the activation of a corona and wind by MHD turbulence in an underlying high-density layer (the photosphere), heating by stochastic resonant acceleration, magnetic reconnection and flares, and shock propagation with associated particle acceleration. We anticipate that as more detailed observations are made of remote objects, similar processes will be identified.

Particle Acceleration and Heating

Collisional shock waves, whether eventuating in a stellar explosion or magnetic reconnection, are a well-known mechanism for heating plasma to a high temperature. As the shock propagates into low-density regions far from its source, it may become collisionless, mediated by wave-particle interactions. Theory predicts power-law particle energy spectra under these circumstances, and consequently, power-law photon spectra. In the case of SN87A, particle energies up to 10^5 GeV have been inferred; however, a review of conditions in various types of objects suggests that shock acceleration will rarely produce particles with energies above 10^6 GeV.

Stochastic resonant acceleration by a variety of waves which can be present in a magnetized plasma gives a quantitative account of the spectra of solar flares. Although the ultimate energy source must be magnetic reconnection, how the waves are generated in the reconnection region is an open question. One candidate is Alfvén waves excited in the reconnecting magnetic field and propagating into the surrounding plasma. Such waves may also be implicated in driving the solar wind.

Magnetic reconnection has been directly observed in the earth's magnetotail, where lines of force of opposite polarity are driven together. There are at least two important parameters: the speed v_m at which fields of opposite polarity merge as reconnection proceeds, and the energy spectrum of emergent particles (for example, predominantly thermal versus nonthermal). Observations suggest that this is different in different cases.

The ratio of v_m to the Alfvén speed v_A in the reconnection region is certainly less than or equal to unity. Various models predict different values for this ratio. The classical Sweet-Parker model predicts $R_M^{-1/2}$, where R_M is the magnetic Reynolds number. The Petschek model predicts $(\ln R_M)^{-1}$. Since R_M is usually $\gg 1$ in astrophysics, these predictions are very different; for example, if $R_M = 10^8$, the first is 10^{-4}, while the second is 0.05. The observational evidence suggests that in astrophysics the larger value applies. Recent numerical simulations with classical resistivity give the Sweet-Parker value, while those with anomalous resistivity due to current-driven instabilities give the Petschek value.

Shock acceleration is not the only way to accelerate particles. The huge electric fields developed in the rotating magnetic field of a pulsar are also effective, and may well account for high-energy cosmic rays. However, there is difficulty in accounting for the energy of particles with energies exceeding 10^{11} GeV observed in air shower experiments by any known astrophysical environment.

Disks and Jets

Accretion disks are inferred from observations of protostars, X-ray binaries, and AGN, to name a few examples, so a proper understanding of disk physics is essential. Jets and winds are also observed in the same types of sources. At this symposium, we learned that both phenomena can be understood as the result of magnetic fields in accreting plasma. Balbus and Hawley realized that an imbedded magnetic field causes a Keplerian disk to become unstable, as growing magnetic torques release the gravitational energy of orbiting plasma. We learned that current simulations indicate that even a small-scale disordered field can do this, growing to approximate equipartition with turbulence in the process. The resulting turbulent stress, partly magnetic and partly kinetic, resolves the long-standing problem of what provides the effective viscosity in accretion disks.

If the disk is like the solar photosphere, one may expect similar magnetic activity above it: flares, corona, and wind. Indeed, a superhot corona (10^9 K) is needed in most models of X-ray sources to inverse Compton scatter thermal photons from the disk into the X-ray region. Flares may explain the observed time variability, and a wind can supply the plasma that is collimated to form a jet.

At this symposium, we heard about simulations of jet collimation due to the pinch forces in an underlying poloidal magnetic field twisted by the rotation of a disk. Some of the simulations presuppose a large-scale poloidal field which exists independently of the disk. Alternatively, dynamo action in the disk may create the disk's own poloidal field, which, when twisted, can collimate a wind into a jet.

An important step forward is extension of simulations of disks and jets to space times near a black hole. In one such simulation, it was found that plasma within $r = 6\,M$ is shock heated and ejected. This result seems broadly consistent with observations of very broad Kα lines in some AGN.

The theory that the X-rays in Seyferts are due to Comptonization in a thermal plasma has been verified by observing the expected exponential cutoff in the spectrum. The next step is to identify the energy source which heats the plasma to 10^9 K. If it is ultimately magnetic reconnection, the heating may be due to stochastic resonant heating, as in solar flares. If the accelerated particles are nonthermal, they can be thermalized by the synchro-Compton process.

There was relatively little discussion of advection-dominated accretion flows (ADAFs), which have been proposed to account for those cases like the source at the galactic center, where both a supermassive black hole and a gas supply are present, so accretion is probably occurring, but the luminosity is low. A key requirement of such a model is that only a tiny fraction of the accretion energy can be deposited in the electrons, as they can radiate the accretion energy away. The great bulk of the energy goes into the ions, which carry it with them into the black hole. One speaker adduced arguments that the required level of inefficiency of energy transfer to the electrons is at odds with expectations from plasma physics, but this remains an open issue.

Gamma-Ray Bursts

There are two classes of gamma-ray bursts—those of long or short duration. Those of long duration have now been proved to be at cosmological distances by measuring the redshift of galaxies known to be in front of their afterglows. The cosmological distances place lower limits on the total energy involved for a given level of assumed beaming of the gamma radiation. We heard evidence supporting a beamwidth of the order of 0.1 radians in some sources, but it was not clear if this can bring energy estimates down to a reasonable 10^{52} erg for all known long-duration bursts. We were reminded at this conference that afterglows of short-duration bursts have not been detected, so it is not possible yet to assign secure distances to them.

A model based on synchrotron emission by electrons in internal shocks in a $\gamma \sim 100$ fireball agrees well with the observed time and frequency behavior of observed bursts. The underlying energy source is still unknown. However, two promising hypotheses were discussed at this meeting. In the first, a torus of matter orbits a neutron star or black hole following a collision. In the other, the explosion of a very massive star yields a hypernova.

We heard that afterglows were observed just before the symposium, on July 4 and on July 5. The significance of the first is obvious, but the second seems surprising. How did nature know that July 5 is a holiday in Bozeman?

Other Objects

We learned that it is now possible to accurately separate accreting stellar black holes from neutron stars on the basis of their X-ray spectra. About 10 of the former are now known. There is a wide variety of accreting neutron stars. Their types appear to be determined by the magnetic field of the star, ranging from 10^9 G to 10^{14} G.

There is a debate concerning the fate of the rotational energy lost by pulsars. The rotational energy of the Crab pulsar seems to be going into the nebula via a relativistic wind, but in other cases it is known only that the observed radiation is a small fraction of the total. Could relativistic winds be the norm? If so, why are they so inefficient at radiating?

A model for gamma-ray repeaters based on a neutron star with a field of 10^{14} G was presented. A quake in the star shakes the field lines, accelerating particles that then radiate.

One of the largest known energy pools is the 10^{64} erg that resides in the hot (~ 10 keV) intracluster gas of galaxies. In many clusters, the density is high enough at the center that bremsstrahlung cooling to below 1 keV is effective, and up to $10^3\,M_\odot$ per year is cooling this way. Apparently, those clusters without cooling are those in which the cooling flow is interrupted by ongoing mergers with other material. A quantitative theory fits the data well.

Finally, attention was drawn to the fact that Faraday rotation measurements demonstrate the existence of large-scale magnetic fields in some clusters, with magnetic fluxes of the order of $10^4\,\mathrm{kpc}^2\,\mu\mathrm{G}$. If magnetic flux is conserved, it is hard to attribute this to the flux originally stored in a spiral galaxy, usually less than 10 in the same units. It was proposed that this flux may emerge in a galactic jet and have its ultimate origin in a dynamo operating in the accretion disk around a supermassive black hole.

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