N87-24251

4

THE ENERGY SOURCE OF THE INTERPLANETARY MEDIUM AND THE HELIOSPHERE

Eugene N. Parker
Enrico Fermi Institute and
Department of Physics
University of Chicago
Chicago, Illinois 60637

ABSTRACT

The activity of the interplanetary medium arises from occasional transient outbursts of the active corona and, for the most part, from the interaction of fast and slow streams in the solar wind. The basic driver is the heat input to the corona, both transient and steady. The fast streams issue from coronal holes where the heat input may be Alfvén waves with root mean squared (rms) fluid velocities of nearly 10^2 km/sec or may be wholly or in part the waves refracted into the hole from neighboring active regions. If the latter, then the character of the wind from the coronal hole depends upon the proximity and vigor of active regions, with significant differences between the polar and low latitude solar wind. In any case, there is no observational support for any of these ideas, so that the primary cause of the wind from the Sun, as well as any other similar star, is not without mystery. It is to be hoped that ground-based observations together with the new input from the Solar Optical Telescope and the International Solar Polar Mission may in time succeed in clearing up some of the basic questions.

1. INTRODUCTION

The interplanetary medium, and the entire heliosphere, are a consequence of the continual expansion of the solar corona. The activity of the interplanetary medium arises from the occasional transient heating of the corona, and the mixture of fast and slow regions of wind from different parts of the corona. The basic energy source is the occasional flare and the coronal heating that maintains the temperature of the corona. It is the purpose of this presentation to review what we know and do not know of the heating.

The expansion of the corona follows from its high temperature, and it is generally accepted that the high temperature is caused by the dissipation of motions initiated in the convective zone. The difficulty is that the motions, and their ultimate dissipation in the corona, have proved elusive.

The corona is conveniently classified into three distinct regions, depending upon the intensity of the X-ray emission. There is the active X-ray corona ($N = 10^{10}$ atoms/cm^3, $T = 2.5 \times 10^6$ K, $B = 10^2$ gauss), requiring an energy input of about 1×10^7 ergs/cm^2 sec [Withbroe and Noyes, 1977]. The gas is confined in the closed bipolar magnetic field, so that most of the energy goes into radiation and thermal conduction downward into the transient region. There is the quiet corona, emitting a faint glow of X-rays ($N = 10^8$ atoms/cm^3, $T = 1.5 \times 10^6$ K, $B = 10$ gauss) maintained by an energy input of 3×10^5 ergs/cm^2 sec). Finally there is the tenuous coronal hole, conspicuous by the absence of X-ray emission ($N = 0.5 \times 10^8$ atoms/cm^3, $T = 1.5 \times 10^6$ K, $B = 10$ gauss) requiring an energy input of about 1×10^6 ergs/cm^2 sec [Zirker, 1977; Withbroe and Noyes, 1977; Leer, Holzer, and Fla, 1982; and Withbroe et al., 1985]. The magnetic field of the coronal holes opens outward into space, permitting free expansion of the coronal gas, so that most of the energy goes into production of the solar wind.

The fast streams in the solar wind come from the coronal holes [Hundhausen, 1972; Krieger, Timothy, and Roelof, 1973; Zirker, 1977; and Rottman, Orrall, and Klimchuk, 1982]. Evidently most of the wind, including the slow streams, is produced in and around coronal holes, with the quiet regions contributing to the slow wind [see discussion in Withbroe and Noyes, 1977]. We would expect that the coronal gas on any open field lines contributes to the wind. The lowest energy state for the magnetic field is a closed configuration, so the field is open only where it is sufficiently weak to be pushed out by the pressure of the coronal gas [Parker, 1963]. The division between the active and the quiet corona may depend as much upon the closure of the magnetic field as upon the field strength.

A close examination of the mechanisms available for heating the corona suggests that there are qualitative as well as quantitative differences between active coronal regions and coronal holes. First of all, Rosner, Tucker, and Vaiana [1978], have emphasized that the observations of the active corona, and the theoretical models constructed from those observations, make it clear that (a) the heat input is distributed along the emitting X-ray loops and (b) there is a direct relation between heat input (ergs/cm^2 sec) and magnetic field. The relationship depends very little on the dimensions L of the region [Golub et al., 1980]. Thus, the X-ray bright points (L $\sim$ 10^4 km) have approximately the same surface brightness as the X-ray corona above a normal active region (L $\sim$ 2×10^5 km). The evidence is that the regions of re-entrant, i.e., closed, field, are heated largely through the dynamical nonequilibrium of the wrapping and interweaving of the lines of force, whereas the only known mechanism for heating the coronal regions with open fields is the dissipation of hydromagnetic waves. Thus it seems that it must be the generation and dissipation of magnetohydrodynamic waves that largely produce the solar wind and the heliosphere. The problem is to confirm this general concept with concrete facts.

Observations show wave motions, but with such small amplitudes that they represent no more than 10^5 ergs/cm^2 sec [Athay and White, 1978, 1979a,b; Bruner, 1978]. Hence, if there are enough waves to heat the corona, the scale of the waves must be so small ($<10^4$ km) that they are not resolved in the spectroscopic studies [Cheng, Doschek, and Feldman, 1979; Feldman, 1983; and Habbal, Leer, and Holzer, 1984; see also the results for sunspots, Beckers, 1976; Beckers and Schneeberger, 1977]. Unresolved waves are part of the "microturbulence", contributing to the line widths which place an upper limit of about 25 km/sec on the rms velocity $<v^2>^{1/2}$. Sound waves of this amplitude carry negligible energy because the speed of sound is only about 2×10^2 km/sec. If we assume, then, that the microturbulence is entirely the result of unresolved Alfvén waves all propagating upward along the field, the energy flux is bounded by the upper limit $\rho <v^2> V_A$, where V_A is the Alfvén speed with a value of the order of 2×10^3 km/sec throughout the entire corona. This upper bound is 2×10^7 ergs/cm^2 sec in the active corona but only 10^5 ergs/cm^2 sec in the coronal hole as a consequence of the low density. It is immediately evident that the Alfvén wave amplitude must be much larger, of the order of 75 km/sec, if the coronal hole is to be heated by wave dissipation. We may speculate that the gas density in the coronal hole is so small that its contribution to the observed line widths is negligible when integrated along the line of sight, so that the necessary 75 km/sec rms velocities are undetected. Such velocities are relatively small, in the sense that the ratio of the velocity amplitude to the phase velocity, and the fractional variation $\Delta B/B$ of the magnetic field, are small, approximately 0.05. So perhaps the coronal hole is heated by the dissipation of Alfvén waves, or perhaps fast mode waves, with periods of, say, 100 sec and rms velocities of the order of 50-100 km/sec. But this is only a conjecture.

There are difficulties of another type in the active corona. The upper limit on the total wave flux of 2×10^7 ergs/cm^2 sec is sufficient to supply the active corona, but most of it must be dissipated in the first pass up around the bipolar field. The downward wave flux at the foot points of each re-entrant line of force must not be more than a third of the upward wave flux if the net upward energy flux is to be 1×10^7 ergs/cm^2 sec. What is more, the dissipation must be equally effective over scales ranging from 10^4 km to 2×10^5 km, i.e. Alfvén transit times of 5 to 100 sec. Most of the power in the observed small-scale fluctuations in the Sun lies at periods of 100 sec or more, with no theoretical reason to expect much power at shorter periods. It must be remembered, too, that whatever the distribution of wave power over period, it all contributes directly to the upper limit of 25 km/sec on the rms velocity.

How, then, are we to imagine that the dissipation of Alfvén waves supplies 1×10^7 ergs/cm^2 sec more or less equally to all scales? If, without any theoretical or observational basis, we postulate waves of sufficiently short wavelength as to heat the ephemeral active regions, dissipating over distances of 2×10^4 km, then these same waves dissipating over 2×10^4 km would heat only the lower ends of the normal coronal loops with scales of 2×10^5 km. But Rosner, Tucker, and Vaiana [1978] showed that the heating is broadly distributed, if not entirely uniform, along the X-ray coronal loops. If, on the other hand, we imagine that the small, medium, and large active coronal regions are each heated by waves at different frequencies which just happen to provide the same heat input at all scales from small to large, we violate the observational upper limit of 25 km/sec on the rms gas velocity. For even one such frequency band carrying 1×10^7 ergs/cm^2 sec provides the upper limit of 25 km/sec on the rms gas velocity if it is not dissipated, leaving no room for another band or two, one of which is dissipated to supply the necessary 1×10^7 ergs/cm^2 sec. To see how this works note that a velocity of 25 km/sec is necessary to transport 1×10^7 ergs/cm^2 sec upward along the field. If the waves are not dissipated (and no one knows how to dissipate waves of such small amplitude $\Delta B/B \sim 0.05$ in so short a distance), then they propagate undiminished up around the re-entrant field and back down into the photosphere at the other end. Hence, both ends of the field have upward and downward propagating waves with an rms fluid velocity of 25 km/sec and zero net energy flux. The observational limit of 25 km/sec permits no other waves. So there is no room for undissipated waves. Somehow, then, we would require that waves of small amplitude dissipate more or less *uniformly* and *completely* along fields with lengths anywhere from 10^4 km to 2×10^5 km. To achieve this requires physical effects unknown to this author.

This leaves us with the alternative that the active corona, enclosed in the re-entrant fields of bipolar regions on the surface of the Sun, is heated principally by the current sheets produced by the shuffling and intermixing of the footpoints of the field [Parker, 1979, 1982, 1983a,b, 1984, 1985; Low, 1985]. The dissipation is then the intrinsic dynamical nonequilibrium and continual neutral point reconnection in the current sheets. The input of 1×10^7 ergs/cm^2 sec follows from shuffling of the footpoints at the not implausible speeds of 0.5 km/sec, wrapping the individual flux tubes about their neighbors with pitch angles of the order of 10-20° [Parker, 1983c].

Unfortunately, at the present time there is no observational information available on either the oscillations of the footpoints of the fields (producing Alfvén waves, etc.) or the wandering of the footpoints among the neighboring footpoints (producing the dissipative current sheets). The individual magnetic fibrils are not resolved in ground-based observations, so that their individual motions are simply not known. The determination of the motions of the fibrils is just one of the many fundamental tasks that awaits the Solar Optical Telescope (SOT) in the next decade. Without the SOT the basic motions of the fibrils, and the strain rate within the field, cannot be determined, and the power source of the corona will remain a matter of "not implausible" assumptions, i.e., ignorance. It should be pointed out that the high-speed turbulence and intense jets observed in the corona by Brueckner and Bartoe [1983] and Withbroe, Habbal, and Ronan [1985] may be a direct manifestation of the dynamical nonequilibrium of the current sheets in the corona.

What, then, of the coronal hole—the source of the high-speed streams in the interplanetary medium? Whatever shuffling and intermixing of the footpoints we may imagine, the associated strains propagate outward into interplanetary space at the Alfvén speed, so that the lines of force do not accumulate any significant mutual wrapping and interweaving. There is no formation of current sheets and no significant dissipation. And as already noted, there is no indication of sufficient microturbulence in coronal holes to provide the necessary 10^6 ergs/cm^2 sec, in the form of outward propagating Alfvén waves. Again we will have to turn to the Solar Optical Telescope to provide complete quantitative information on the oscillatory motions of the magnetic fibrils at the photosphere from which we might estimate the amplitude of the waves in the corona. It will be recalled that wave amplitudes (microturbulence) of 50-100 km/sec are required.

While waiting for the SOT we may hope that some ingenious ground-based observation, or more modest space observation, will provide preliminary clues. In the simplest case, Alfvén waves propagating along a slowly varying magnetic field and slowly varying fluid density have a velocity amplitude that varies as $\rho^{-1/4}$. The density decrease from the photosphere, where the number density is of the order of 10^{17} atoms/cm^3, to the coronal hole, where the density is perhaps 10^8 cm^3, is a factor of 10^9. Thus, 0.5 km/sec in the photosphere produces 100 km/sec in the coronal hole. In actual fact the abrupt decline of the gas density, the associated rapid expansion of the individual fibrils to fill all available space, and the dynamical spicule phenomenon together make any quantitative extrapolation from the photosphere a more complicated operation.

Hollweg, Jackson, and Galloway [1982] have treated the propagation of Alfvén waves in coronal holes. More recently Davila [1985] has explored how the waves might boost the wind along to produce the high speed streams [Holzer and Leer, 1980; Leer and Holzer, 1980]. He does not discuss the origin of the Alfvén waves.

The role of spicules in coronal heating is an intriguing question [cf. Athay and Holzer, 1982; Withbroe, 1983; and Sterling and Hollweg, 1984], although it would appear that their effects do not extend more than 5×10^4 km above the transition region.

Seeking alternatives to direct supply of Alfvén waves to the coronal hole, Fla et al. [1984] have noted the possibility that fast mode waves are refracted into the hole from a neighboring active coronal region [Habbal, Leer, and Holzer, 1979]. The authors have provided a quantitative exposition of the phenomenon. The magnitude of the effect needs to be established in some way from observation. An obvious question is whether the vigor of the high-speed streams in the solar wind reflect the proximity of active regions to the coronal holes throughout the 11-year cycle of activity. Generally speaking, the coronal holes at low latitudes are closer to active regions than the polar coronal holes, so that a direct comparison of low altitude fast streams with the polar wind [cf. Orrall, Rottman, and Klimchuk, 1983] should be instructive. The International Solar Polar Mission (ISPM) will provide fundamental information on this question. Indeed the entire picture of the connection of high-speed streams at low latitudes to the polar coronal holes will be examined by the ISPM. At present we know only that the stream activity at the solar equator correlates best with the magnetic fields and coronal structure at latitudes $\pm 30°$ from the work of Wilcox and others [Wilcox, 1968; Svalgaard, Wilcox, and Duvall, 1974; Svalgaard and Wilcox, 1975; Svalgaard, et al., 1975; and Hundhausen, 1977].

Whatever the source of the waves, it is difficult to imagine heating coronal holes by any means other than the dissipation of magnetohydrodynamic waves.

The dissipation poses no evident problem. The coronal holes are heated gently over long distances ($10^{11} - 10^{12}$cm) out into space. Over such extended scales the Alfvén propagation times are 5×10^2 to 10^4 sec, i.e., 5 to 100 times the 100 sec wave period. There is sufficient time for a variety of dissipation effects to develop, e.g. nonlinear steepening [Hollweg, Jackson, and Galloway, 1982] phase mixing, Landau damping of the fast and slow modes [Barnes, 1966, 1969, 1974, 1979; Barnes, Hartle, and Bredekamp, 1971; Hung and Barnes, 1973 a, b, c; and Habbal and Leer, 1982]. A plane transverse Alfvén wave with small fluid motion $\vec{v}$ ($|\vec{v}| << V_A$) does not damp significantly. But if the Alfvén speed V_A varies in the transverse direction of the fluid motion $\vec{v}$ ($\vec{v} \cdot \nabla V_A \neq 0$), the wave becomes oblique, with a longitudinal component, which is then subject to damping. Indeed, any Alfvén wave of limited transverse scale has a longitudinal component which is subject to Landau damping. So the primary question appears to be the existence of sufficiently strong hydromagnetic waves, and the sources of such waves. Thus it is of primary importance to confirm or deny the existence of waves of 50-100 km/sec amplitude, which is a difficult, if not impossible, task because the coronal holes are so tenuous. Studies of the active and quiet coronas around the periphery of the coronal hole may be informative, in view of the ideas put forth by Fla et al. [1984].

In conclusion it seems to be that the heating of the coronal hole is not without mystery. The energy supply responsible for both the fast and slow streams is simply not clear. This is a fundamental gap in our understanding of the origin and the activity of interplanetary space in particular and stellar physics in general.

This work was supported by the National Aeronautics and Space Administration under grant NGL-14-001-001.

REFERENCES

Athay, R. G., and Holzer, T. E., 1982, *Astrophys. J.*, **255**, 743.

Athay, G., and White, O. R., 1978, *Astrophys. J.*, **266**, 1135.

Athay, G., and White, O. R., 1979a, *Astrophys. J.*, **229**, 1147.

ORIGINAL PAGE IS
OF POOR QUALITY

Athay, G., and White, O. R., 1979b, *Astrophys. J. Supp.*, **39**, 333.

Barnes, A., 1966, *Phys. Fluids*, **9**, 1483.

Barnes, A., 1969, *Astrophys. J.*, **155**, 311.

Barnes, A., 1974, *Adv. Electronics Electron Phys.*, **35**, 1.

Barnes, A., 1979, in *Solar System Plasma Physics*, Vol. I, ed. E. N. Parker, C. F. Kennel, and L. J. Lanzarotti (New York: North Holland), pp. 249-319.

Barnes, A., Hartle, R. E., and Bredekamp, J. H., 1971, *Astrophys. J. Letters*, **166**, L53.

Beckers, J. M., 1976, *Astrophys. J.*, **203**, 739.

Beckers, J. M., and Schneeberger, T. J., 1977, *Astrophys. J.*, **215**, 356.

Brueckner, G. E., and Bartoe, J. D. F., 1983, *Astrophys. J.*, **272**, 329.

Bruner, E. C., 1978, *Astrophys. J.*, **226**, 1140.

Cheng, C. C., Doschek, G. A., and Feldman, U., 1979, *Astrophys. J.*, **227**, 1037.

Davila, J. M., 1985, *Astrophys. J.*, **291**, 328.

Feldman, U., 1983, *Astrophys. J.*, **275**, 367.

Fla, T., Habbal, S. R., Holzer, T. E., and Leer, E., 1984, *Astrophys. J.*, **280**, 382.

Golub, L., Maxson, C., Rosner, R., Serio, S., and Vaiana, G. S., 1980, *Astrophys. J.*, **238**, 343.

Habbal, S. R., and Leer, E., 1982, *Astrophys. J.*, **253**, 318.

Habbal, S. R., Leer, E., and Holzer, T. E., 1979, *Solar Phys.*, **64**, 287.

Hollweg, J. V., Jackson, S., and Galloway, D., 1982, *Solar Phys.*, **75**, 35.

Holzer, T. E., and Leer, E., 1980, *J. Geophys. Res.*, **85**, 4665.

Hundhausen, A. J., 1972, *Coronal Expansion and the Solar Wind* (New York: Springer-Verlag).

Hundhausen, A. J., 1977, in *Coronal Holes and High Speed Wind Streams* (Boulder, CO: Colorado Associated University Press), pp. 292-319.

Hung, R. J., and Barnes, A., 1973a, *Astrophys. J.*, **180**, 253.

Hung, R. J., and Barnes, A., 1973b, *Astrophys. J.*, **180**, 271.

Hung, R. J., and Barnes, A., 1973c, *Astrophys. J.*, **181**, 183.

Krieger, A. S., Timothy, A. F., and Roelof, E. C., 1973, *Solar Phys.*, **29**, 505.

Leer, E., and Holzer, T. E., 1980, *J. Geophys. Res.*, **85**, 4681.

Leer, E., Holzer, T. E., and Fla, T., 1982, *Space Sci. Rev.*, **33**, 161.

Low, B. C., 1985, *Solar Phys.*, **100**, 309.

Orrall, F. Q., Rottman, G. J., and Klimchuk, J. A., 1983, *Astrophys. J. Letters*, **266**, L65.

Parker, E. N., 1963, *Interplanetary Dynamical Processes* (New York: John Wiley and Sons).

Parker, E. N., 1979, *Cosmical Magnetic Fields* (Oxford: Clarendon Press).

Parker, E. N., 1982, *Geophys. Astrophys. Fluid Dyn.*, **22**, 195.

Parker, E. N., 1983a, *Geophys. Astrophys. Fluid Dyn.*, **23**, 85.

Parker, E. N., 1983b, *Geophys. Astrophys. Fluid Dyn.*, **24**, 79.

Parker, E. N., 1983c, *Astrophys. J.*, **264**, 642.

Parker, E. N., 1984, in *Proceedings of III Trieste Workshop on Relations Between Chromospheric-Coronal Heating and Mass Loss in Stars, Sacramento Peak Observatory, 18-25 August*, ed. R. Stalio and J. B. Zirker, pp. 301-17.

Parker, E. N., 1985, *Geophys. Astrophys. Fluid Dyn.*, in press.

Rosner, R., Tucker, W. H., and Vaiana, G. S., 1978, *Astrophys. J.*, **220**, 643.

Rottman, G. J., Orrall, F. Q., and Klimchuk, J. A., 1982, *Astrophys. J.*, **260**, 326.

Sterling, A. C., and Hollweg, J. V., 1984, *Astrophys. J.*, **285**, 843.

Svalgaard, L., and Wilcox, J. M., 1975, *Solar Phys.*, **41**, 461.

Svalgaard, L., Wilcox, J. M., and Duvall, T. L., 1974, *Solar Phys.*, **37**, 157.

Svalgaard, L., Wilcox, J. M., Scherer, P. H., and Howard, R., 1975, *Solar Phys.*, **45**, 83.

Wilcox, J. M., 1968, *Space Sci. Rev.*, **8**, 258.

Withbroe, G. L., 1983, *Astrophys. J.*, **267**, 825.

Withbroe, G. L., Habbal, S. R., and Ronan, R., 1985, *Solar Phys.*, in press.

Withbroe, G. L., Kohl, J. L., Weiser, H., and Munro, R. H., 1985, *Astrophys. J.*, **297**, 324.

Withbroe, G. L., and Noyes, R. W., 1977, *Annual Rev. Astron. Astrophys.*, **15**, 363.

Zirker, J. B., 1977, in *Coronal Holes and High Speed Wind Stream*, ed. J. B. Zirker (Boulder, CO: Colorado Associated University Press).