NASA-CR-191357

HQ GRANT
IN-92-CR
133983
P 13

FINAL TECHNICAL REPORT

for

NASA GRANT NSG-7411

"Theoretical Studies of the Physics of the Solar Atmosphere"

to the
University of New Hampshire

Joseph V. Hollweg 12/11/92

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(NASA-CR-191357) THEORETICAL STUDIES OF THE PHYSICS OF THE SOLAR ATMOSPHERE Final Report (New Hampshire Univ.) 13 p

N93-15085

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"Theoretical Studies of the Physics of the Solar Atmosphere"

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Prof. Joseph V. Hollweg, P.I.

Work done under this grant achieved significant advances in our theoretical basis for understanding several physical processes related to dynamical phenomena on the sun. We have advanced a new model for spicules and fibrils. We have provided a simple physical view of resonance absorption of MHD surface waves; this allowed an approximate mathematical procedure for obtaining a wealth of new analytical results which we applied to coronal heating and p-mode absorption at magnetic regions. We provided the first comprehensive models for the heating and acceleration of the transition region, corona, and solar wind. We provided a new view of viscosity under coronal conditions. We provided new insights into Alfvén wave propagation in the solar atmosphere. And recently we have begun work in a new direction: parametric instabilities of Alfvén waves.

1. Spicules and Fibrils.

In previous work ([1]) we proposed the "rebound-shock model" for solar spicules. In this model a photospheric impulse leads to an oscillating wake which steepens into a shock train. Repeated interactions of the shocks with the chromosphere-corona transition region (TR) eject the TR and underlying chromosphere upwards. This new idea was explored numerically, and we found that structures which resemble spicules in many ways could develop.

Sterling and Hollweg ([2]) developed this idea further and showed how varying the parameters of the problem could lead to structures with properties which agree quite well with the observed properties of spicules. They also found that at long times the system finds a new equilibrium consisting of an extended chromosphere; radiative cooling (not included in the model) would be required to allow the chromosphere to fall back to normal heights. The paper also provided some new analytical results for the impulse response of the solar atmosphere.

In a later paper, Sterling and Hollweg {[3]} showed how the same rebound shock mechanism could lead to fibril structures on 'horizontal' magnetic field lines.

Sterling and Hollweg {[4]} also examined the heating of spicules, which is needed to overcome the adiabatic cooling of the expanding chromospheric material. In the rebound shock model, the shocks provide the heating, but they also examined the heating which could be provided by Alfvén waves. It was shown that spicules can act as resonant cavities which trap waves, allowing large amplitudes to build up. MHD turbulence was shown to be an effective dissipation mechanism, and it was suggested that some spicules fade from view in Hα because the heating could be sufficient to ionize the neutral hydrogen.

This work was the basis of the PhD. thesis of Dr. Alphonse Sterling.

Finally, we considered the ability of Alfvén waves to generate the slow shocks which seem to be the best candidates for driving spicules. Hollweg showed {[5]} that even simple Alfvénic pulses can lead to a sequence of slow shocks and to complicated dynamic motions of the chromosphere and transition region; but the computed structures did not match spicules very well. On the other hand, we found that even a simple Alfvénic pulse can nonlinearly lead to very 'bursty' dynamics of the chromosphere and corona. The Poynting flux into the corona can occur primarily in bursts about 5 minutes apart, and the maximum velocities in the corona are similarly bursty. The net energy entering the corona turned out to be close to what is required to drive the solar wind and heat coronal holes (the model was done for an open field region similar to a typical coronal hole). We were led to suggest that not every impulsive event on the sun needs to be reconnection-related: nonlinear wave dynamics can create impulsive dynamics too!

2. Wave Propagation in the Chromosphere and Corona.

One of the key issues in wave models of chromospheric and coronal heating is the ability of waves to carry the required energies in spite of their strong tendency to be reflected by the Alfvén speed gradient. In previous work we showed how coronal active region loops could act as resonant cavities and enhance the wave energy flux, in analogy with anti-reflection coatings on camera lenses {[6;7;8]}. In work under this grant we applied the idea to spicules {[4]}, and wrote an extensive review {[9]} which corrected the errors in Ionson's circuit model {[10]}.

We also considered the behavior of Alfvén waves in the chromosphere {[11]}. By solving the wave equation, we showed that the observed non-thermal motions in the chromosphere are consistent with the presence of waves. We also showed that turbulent dissipation at the Kolmogorov rate could account nicely for the observed chromospheric heating.

Hollweg and Lee {[12]} considered the effect of solar wind flow and the boundary condition at the Alfvén critical point on the propagation of very low-frequency Alfvén waves. They found that the waves evolve very differently than in the WKB limit which is usually used.

Issues concerning Alfvén wave propagation and dissipation were reviewed in {[13]} and {[14]}.

3. Models for the Transition Region, Corona, and Solar Wind

We have already mentioned that dissipation of MHD turbulence at the Kolmogorov rate yields reasonable heating rates for the chromosphere and spicules. It turns out that a Kolmogorov spectrum of Alfvén waves is observed in the solar wind, and that the observed proton heating in the solar wind is also consistent with wave dissipation at the Kolmogorov rate. Rough estimates also indicate that Kolmogorov dissipation is consistent with the required heating in the coronal active region loops and coronal holes as well {[9]}.

We tested the idea that the high-speed solar wind, the coronal holes from which the wind originates, and the underlying transition region are all driven by a single process, viz. the dissipation of Alfvén waves at the Kolmogorov rate and the attendant wave pressure forces. Hollweg {[15]} produced a one-fluid model, and Hollweg and Johnson {[16]} produced a two-fluid model incorporating waves, electron heat conduction, and optically thin radiation. They found that dissipating Alfvén waves could indeed produce a steep temperature rise (the transition region) to coronal temperatures, and a solar wind flow. But although the models came close to explaining most of the observed features, it failed in detail. If parameters were adjusted to give a high-speed wind, then the coronal pressure was somewhat too low; if the parameters were adjusted to give the observed coronal pressure, then the wind was somewhat too slow. But the worst failure was a prediction that the proton temperature would be about 3×10^6 K at $r = 3r_{sun}$; UV observations suggest that such a large proton temperature does not exist. However, the model has many desirable features, and we believe it is possible that a more sophisticated treatment of the spatial evolution of the turbulence could bring things in line with the data. This is work for the future.

A review of recent solar wind models is given in {[17]}. Some basic ideas about MHD turbulence were reviewed in {[18]}.

4. Resonance Absorption of MHD Waves.

Another mechanism for dissipating waves and heating the corona was suggested by Ionson ([19]). This mechanism is called "resonance absorption". Lee and Roberts ([20]) used a very special case to elucidate how energy can be transferred from a global surface mode into a thin energy-containing layer. Strong gradients build up in the layer, and even a small amount of viscosity or resistivity can convert the energy into heat.

In ([21]), Hollweg provided the first simplified physical picture of the physics underlying resonance absorption. He showed that the "resonant field lines" behave as simple harmonic oscillators which are driven by the total pressure perturbations associated with the global surface wave. This simple model easily explained all the features found by Lee and Roberts. It showed (contrary to what many workers have stated) that "phase mixing" does not cause resonance absorption; the opposite is true since phase mixing destroys the phase relationship between the driven oscillators and the driver, which is necessary for the resonance. Our physical insight also allowed us to obtain many new analytical results via a new procedure which is *much* simpler than the methods used by Ionson, Lee and Roberts, and many other workers.

For example, Hollweg ([22]) included viscosity (or electrical resistivity) without the difficult matched asymptotic expansions attempted by others. For the first time, he verified Ionson's conjecture that the heating rate can be independent of viscosity or resistivity.

Hollweg and Yang ([23]) extended the procedure to the compressible plasma, and obtained a wealth of new analytical results for the damping rate due to resonance absorption (along the way, they corrected a key result of Ionson). They concluded that resonance absorption is a viable coronal heating mechanism. They also made the suggestion that resonance absorption could nonlinearly drive Kelvin-Helmholz instabilities and MHD turbulence. This suggestion was later verified numerically by Uchimoto et al. ([24]). The instabilities and turbulence could be a means of spreading out the heat in a coronal loop. These ideas were reviewed in ([18]) and ([25]).

A modification of our new procedure was used by Hollweg, Yang, Cadez and Gakovic ([26]) and by Yang and Hollweg ([27]) to investigate the effects of velocity shear on resonance absorption. (The modification makes the mathematics identical to the well-known procedure used in calculating Landau damping.) We discovered a new *resonant* instability driven by velocity shear. The instability threshold is below that of the nonresonant Kelvin-Helmholz instability. The physics of this new instability, and its nonlinear development, remain topics for the future. In any case, Yang and Hollweg found that velocity shear can increase or decrease the resonance absorption rate, but they concluded that resonance absorption remains a viable candidate for coronal heating. (Along the way, Yang and Hollweg also provided some new analytical results for the Kelvin-Helmholz threshold.)

Yang's work on resonance absorption was the basis of his PhD thesis. He received the PhD in May 1993.

Most of our analytical results for resonance absorption of surface waves assumed that the "surface" is thin. Absorption by thick surfaces in general requires a full solution to either a wave equation, or an initial value problem (as in Lee and Roberts). But Hollweg {[28]} used a novel (clever) technique to circumvent the initial value problem. He calculated resonance curves for a "driven" surface, and noted that the curve width corresponds to the decay rate of the undriven system (i.e. the initial value problem). For the first time, surface wave decay rates for thick surfaces were easily obtained. The conclusion was, again, that resonance absorption is a viable mechanism for coronal heating.

We also considered the absorption of propagating waves which impinge on a region where the plasma parameters spatially vary. Our original effort {[29]} was directed at understanding a result of Uberoi {[30]}, which seemed to disagree with our basic driven harmonic oscillator view of resonance absorption; we found that Uberoi's paper was incorrect, and that our view is valid. We also found that fast waves could be efficiently absorbed by coronal structures. If fast waves exist in the corona (but this is unlikely) they could contribute to coronal heating.

Hollweg {[31]} applied these results to the observed absorption of sound waves by sunspots. He found that resonance absorption can in principle account for the observed absorption, but only if the sound waves impinge on the sunspot boundary with angles of incidence within a specified range. One of the criteria is in fact satisfied near the solar surface, where the sound waves propagate nearly vertically. But it is not clear if a second condition is satisfied. However, Hollweg suggested that resonantly absorbed sound waves might reappear as the running penumbral waves; this suggestion remains to be tested observationally.

The above calculations were all done using planar geometry. Hollweg, working with Goossens and Sakurai, extended the calculations to cylindrical geometry {[32;33]}. It turns out, happily, that all results for coronal heating of active region loops remain intact; all one has to do is make a simple replacement of wavenumber k with azimuthal order m.

Sakurai, Goossens, and Hollweg {[34]} re-examined the absorption of sound waves by sunspots, using cylindrical geometry. Absorption coefficients were calculated analytically under certain simplifying conditions, and numerically under more general conditions. We found that reasonable choices of parameters could yield absorption coefficients in excess of 50 percent. The observed absorption coefficients are of this magnitude. (Along the way, we found that the m-dependence derived by Chitre and Davila {[35]} is incorrect.)

In a more recent paper, Goossens and Hollweg {[36]} found that total absorption (i.e. an absorption coefficient of 100 percent) of sound is possible. This occurs when the impinging sound excites a normal mode of a magnetic flux tube; total absorption can occur when there is an impedance matching between the damping associated with resonance absorption and the damping associated with radiation of sound by the eigenmode. The absorption coefficient can be a strongly peaked function of frequency. If such peaks can be observed, they would provide a means of deducing the eigenfrequencies and thus the plasma and magnetic properties of the flux tube. This interesting possibility remains to be exploited.

5. Parametric Instabilities.

We have recently started what promises to be an extensive series of investigations of parametric instabilities. We have been looking at the instabilities of large-amplitude Alfvén waves, which are observed to be ubiquitous in the solar wind.

One of our motivations has been to explain the solar wind heavy ion problems: the ions flow faster than the protons by about the Alfvén speed, and the ions are hotter than the protons in proportion to their masses. Our basic idea was to ask whether parametric instabilities can take energy and momentum out of an Alfvén wave and dump it into the ions. The first step was to calculate, for the first time, parametric instabilities in the presence of streaming He^{++} (the most abundant heavy ion). Hollweg, Esser, and Jayanti ([37]) found a wealth of new instabilities which would not exist in the absence of streaming He^{++}. Some of these instabilities are near the He^{++} cyclotron resonance, and it seems possible that the ions could absorb some of the energy in the instability. Other instabilities may be able to dump energy into the ions via a Landau resonance. But much work still needs to be done to see if these preliminary ideas will hold water.

We also re-examined the dispersion relation for the stability of parallel-propagating Alfvén waves in the absence of He^{++}. Jayanti and Hollweg ([38]) realized that a proper analysis should use Floquet's theorem, which had not been done. They found an infinite hierarchy of dispersion relations, but they were all equivalent; the only differences were due to redefinitions of the meanings of ω and k. Jayanti and Hollweg concluded that some "new" dispersion relations presented by Viñas and Goldstein ([39]) are incorrect, and that some "new" instabilities found by Viñas and Goldstein don't exist.

6. Physical Processes

a. Viscosity. In the solar corona there are five viscosity coefficients. Only one of them, denoted η_0 by Braginskii {[40]} is large enough to be of interest in the corona. Hollweg {[41;42]} examined the physical meaning of η_0, and when Braginskii's derivation is valid. It was found that η_0 arises simply from the tendency of $p_{||}$ and $p_{\perp}$ to become slightly unequal, and a simple rederivation of η_0 was presented. However, η_0 is associated with plasma compressions and rarefactions, and we were unable to find cases where coronal compressions are large enough for η_0 to yield significant coronal heating -- a big disappointment.

b. Nonlinear Surface Waves. We have already discussed the importance of MHD surface waves and resonance absorption for coronal heating. Hollweg {[43]} undertook a study of the nonlinear development of incompressible surface waves. The method employed was similar to how one studies nonlinear ocean waves, but the analysis turned out to be vastly more complicated. It was found that MHD surface waves can steepen or they can develop peaked crests or troughs. This is in contrast to deep ocean waves, which only develop peaked crests.

c. WKB Analysis. Hollweg {[44]} re-examined the WKB expansion for Alfvén waves in the solar wind. He found that the analyses used previously are nonuniformly convergent, and he provided a new analysis using the method of multiple scales. One result was that an outward-propagating wave has both Elsässer variables δz^+ and δz^-, which are required for the evolution of MHD turbulence. However, with few exceptions, the predicted power spectra for δz^+ and δz^- do not agree with the observed spectra in the solar wind. Thus the turbulence in the solar wind is more fully developed than can be accounted for by a WKB analysis.

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