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"CORONA: COORDINATED RESEARCH ON NON-THERMAL PROCESSES IN ASTROPHYSICS"

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FINAL REPORT ON NASA GRANT NAGW-1295: "CORONA": COORDINATED RESEARCH ON NON-THERMAL PROCESSES IN ASTROPHYSICS

The purpose of this grant was to examine several problems in astrophysics where departures from purely thermal behavior are expected to produce effects which are detectable by a variety of NASA satellites. The problems which we identified as worthy of investigation included coronal heating in stars, deposition of non-thermal particle energy in stars from external sources, and turbulence in atmospheres and winds of stars.

Significant progress was made in various aspects of these problems during the three-year lifetime of the grant. We summarize this progress in what follows.

1. Coronal heating.

Cool stars of many spectral types exhibit evidence for gas at millions of degrees K, indicating deposition of mechanical energy. The ultimate source of this energy is convection, and the ultimate deposition source in the corona resides in magnetic structures of various kinds.

(a) Convection simulation

The general problem of convection is one of great complexity, including driving of convection, scale selection, mixing and turbulent transfer, interaction with magnetic flux tubes, and radiative transfer effects. A major effort of our work in the past three years has been to develop a code to simulate 3-D compressible convection. Dr Murshed Hossain was hired as a Research Associate in October 1988 to develop the code. Within 6 months, he had a code running on a CYBER 205, and then he developed it for an IBM 3090, and finally for Cray computers in San Diego and University College London.

In contrast to many existing stellar convection codes (which are based on finite difference [FD] methods), ours is based on pseudo-spectral methods. The significant advantages of spectral methods over FD methods in describing flows are well documented: to achieve a 1% error in a particular 1-D flow, a second- order FD code requires 10-15 times as many grid points as a spectral method (Go77). Moreover, by using Chebyshev collocation in the vertical direction, we resolve small spatial scales at the top, and preserve accuracy in evaluating energy and momentum fluctuations where these are largest (near the bottom). Our code also enables us to follow sound waves explicitly. To include the whole convection zone with free boundaries in the computational domain is not feasible: the outer solution is not known. Overshoot and undershoot make the problem even more complicated. This calls for a model of an artificial computational boundary. Some earlier simulations were performed with artificial solid boundaries. Later simulations attempted to model artificial open boundaries. In our code, attention has been paid to modelling the top/bottom boundaries as realistically as possible in the stellar context: not only do the boundary velocities satisfy stress-free conditions, but we also demand that the horizontal averages of top/bottom pressure and density remain equal to their initial values. First results from this code were published in 1990 (Ho90a). An extensive report on our simulation of convection zones of progressively increasing depths is now in press in the Astrophysical Journal: this report will run to 25-27 pages in print.

When our solutions evolve into statistically steady state, the enthalpy flux is upward, the net kinetic energy flux is downward, the maximum Mach numbers are comparable to solar values, and there is a global vertical structuring in the flow, with smaller "cells" on top of larger "cells" and a preferred spatial scale remarkably close to Hp, as MLT assumes. The heat fluxes in the deepest of our simulations are not yet large enough to be comparable to solar values. We need to go to deeper zones. Our code allows us to study the trapping of sound waves in the computational box. Power spectra of our solutions show that certain frequencies are prevalent in the flows, and that these frequencies are related to sound-wave crossing times. An eigenfreqeuncy analysis shows that our computational box is large enough to allow as many as four radial nodes in the vertical direction for the lowest order "spherical harmonic". Thus, we can in a simplified fashion model the trapping of p-modes in stellar convection zones (cf. St89b). It may be that interactions between standing acoustic waves and convective flows control the spatial scales.

In order to resolve all possible scales, the number of 3-D grid points must be unfeasibly large. A practical solution to this closure problem is to simulate directly the large eddies and model the effects of small unresolved scales on them. This LES (large eddy simulation) approach leads to various eddy viscosity models: we use an ad hoc (Smagorinsky) sub-grid model in our code. Recently (Zh88,89), we have studied how elimination of a progressively larger number of short-wavelength modes in a spectral code affects the large-scale dynamics: this has led to a new sub-grid model including non-diffusive effects (Ho90b) which exhibits promising behavior when applied to incompressible homogeneous turbulence.

Because mechanical energy is at the heart of coronal heating, we need to determine the flux of mechanical energy created by our simulated convection. Our simulations currently include a number of spectral modes so that we can evaluate roughly the power spectra (both temporal and spatial) of convective flows in stellar convection zones. Knowledge of the spatial scales is important because for electrodynamical heating of the corona, total fluxes are not enough: spatial scales must also be known (Sp83). We can also determine the total flux of mechanical energy: we find that as the simulated convection zone deepens, the ratio of mechanical energy to thermal flux is of order a percent or so. this is precisely what is needed to explain the heating of coronas in stars where the non-thermal heating is at saturated levels.

(b) Coronal loops.

If resonant absorption (Da87) heats loops, the coupling efficiency between Fmech and the loop depends on lumped parameters of the loop (Sp82) (including t_A, the MHD crossing time: Io84), and the resonant Q-factor is quite modest (Q = 5-10: Ho84). A newly emerged loop being stressed stochastically by convection should require about Q times t_A to "turn on" to full strength, during which its emission may vary with period t_A: later, when a standing wave pattern is in place, the emission should be steadier. In flare stars, loops are so large (Ha83) that a single loop may be discernible in integrated emission. Interestingly, transient quasi-periodicities are seen optically in flare stars (An90), with time-signatures (TS) of minutes or less: significantly, TS are correlated with X-ray luminosity (An89).

During the 3-year period of our grant, the PI has been successful in obtaining observing time during the pointed phase of the ROSAT X-ray satellite. The targets are four of the strongest known X-ray emitters among M dwarfs. The purpose is to search for TS in X-rays in these stars. The observations were performed by the High Resolution Imager on ROSAT in April and May 1991, and we are currently waiting for the data to be sent to us.

While waiting for X-ray data, we have instigated at Delaware a ground-based observing program to search for loop periodicities in coronally active stars using optical data. This work has led to a Master's thesis for S. Bhattacharyya, presentation of results at the IAU General Assembly in Buenos Aires, and a preprint. The periodicities are found to be transient, and are consistent with what would be expected of a rather low quality resonant cavity coronal loop. When our data are interpreted in terms of a damped loop model, we are able to extract densities, temperatures, lengths, and magnetic field strengths in the coronal loops. The results are remarkably similar to those determined from analysis of the few X-ray data which the NASA satellite Einstein obtained in 1980. Thus, our work appears to give us a view into coronas in active stars even if there are no space-borne X-ray detectors available. This must be considered as a very positive development in the study of stellar coronas.

(c) Coronal magnetic reconnection.

An important aspect of our work in coronal heating during the 3-year grant has been to investigate the small-scale structure which occurs in the corona of the sun and similar stars. The smallest structures occur at dissipation scales, and reconnection is a candidate for coronal dissipation (Pa88). Granule velocities and lifetimes determine the scales on which flux tubes are braided and therefore reconnect: 300 km in the Sun. We have investigated in some detail the formation and ejection of plasmoids as the unit events of coronal heating: this has led to the publication of an extensive paper in Astronomy and Astrophysics.

There is considerable evidence that plasmoids are formed in, and ejected from, reconnection sites (Gu89). Plasmoids are particularly important in the context of mass loss because Lorentz forces accelerate them towards weaker fields (Pn83). Thus, in an active region (where fields are certainly nonuniform: Go90a), plasmoids will be guided towards the weakest fields, which are more likely to be open. Plasmoids therefore can contribute to a wind from active regions, unlike the behavior of isolated charged particles. Structure observed in the inner solar wind at 100-1000 km (Co89a) may be due to plasmoids from coronal reconnection sites (Mu90a):

such structures cause intensity scintillations of radio sources. An advantage of a plasmoid-driven wind is that it may experience very rapid acceleration, and this is apparently required in the case of the wind which we have discovered from the K2 dwarf in V471 Tauri (see (e) below).

(d) Far Infrared and Submillimeter studies of coronas.

During the course of this grant, stars in which coronas are most active (flare stars) have been subjected to observation at wavelengths in the far infrared and submillimeter for the first time: these data were obtained because we were successful in submitting proposals to an IRAS data analysis program and to the James Clerk Maxwell Telescope (JCMT).

When all known flare stars were examined in IRAS data, 75 percent were detected at 12 microns, and of these, 20-30 percent were also seen even at 100 microns (Mu89b). At the latter wavelengths, the emission is certainly much stronger than photospheric. The question is: what causes this strong infrared excess? Various sources come to mind. Far-IR emission from flare stars may contain a synchrotron component (Mu89b), implying fast electrons. Flare star coronae are very efficiently heated, possibly by reconnection events, and reconnection sites are efficient accelerators of particles (Ma84). Dust is a possible source of the emission, as is free-free emission from an ionized wind. To address these possibilities, we observed several flare stars with the JCMT at wavelengths of 0.8 and 1.1 millimeters. We have detected some of the stars at the 3 sigma level, and data analysis is now in progress. It turns out that to fit our data with dust emission, the dust would have to be very cool. More promising is the free-free emission from a wind. But in this case, the mass loss rates must be very high, much larger than anyone has claimed before of flare stars. (However, we must admit that no-one has directly detected mass loss from any M dwarf.) Thus, we may have discovered the first evidence for mass loss from M dwarfs (following on to our earlier discovery of mass loss for the first time from a K dwarf in V 471 Tauri (see (e)).

(e) Coronal expansion.

During the course of this grant, an important step forward has been taken in the study of mass loss from cool solar-like stars. A wind from a cool (K2) dwarf has been detected spectroscopically for the first time: the dwarf is in V471 Tauri, a detached binary without Roche lobe overflow. IUE data indicate that the wind is highly structured in velocity, variable on scales of a day, is rather cool, and accelerates very rapidly, reaching 500-600 km/sec on a spatial scale of no more than a few K star radii (Mu89a). Independent evidence for cool material in another K2V corona exists (Co89b). In the solar wind, cool material indicates thermal isolation from the ambient wind (Ne83): cool wind in V471 Tau (K2) may result from ejection of magnetically isolated CME's, and these would also explain velocity structuring and variability. No ambient wind is detectable: CME's appear to dominate the mass flux, unlike the solar wind where CME's carry <10% of the flux (Ho85). To understand this difference, we note that the rotation of V471 (K2) is 50 times faster than solar:

hence, magnetic activity (and associated CME's) is expected to be much stronger than solar. The absorption in certain wind features is very strong in V471 (K2) indicating structures comparable in size to the stellar disk (10^{10}-10^{11} cm). By analogy with the inner solar wind, such CME's are expected to drive an energy cascade to smaller scales, and plasmoids may explain the rapid acceleration (Mu90a).

2. External sources of non-thermal heating in stars

(a) Cygnus X-3

A powerful source of energetic particles from a compact star impinges on the companion star and deposits energy not only in the surface layers (and wind) via charged particle and photon interactions, but also deep inside that star via neutrino interactions. In this situation, and others like it (in active galactic nuclei), the external energy source may be larger than the internal source of energy in the companion star itself, thereby altering completely its structure. Calculations of this effect in Cyg X-3 have led to estimates of evaporation times of the companion star. IN AGN's, stars of mass 0.5 solar masses can be puffed up to red giant size as a result of these energy depositions.

(b) Supernova 1987A

The supernova 1987A has been a fruitful source of study of high energy non-thermal particles. Discussion of particle acceleration to PeV energies, as well as the associated searches for TeV photons from such particles, have been published by members of our group. Acceleration of particles in the standing shock created when a wind of relativistic electron-positron pairs from the pulsar impinges on Acceleration when the pulsar wind impinges on the ejecta is the subject of an extensive paper by members of our group in Astrophysical Journal.

The calculation of π-decay gamma-rays from cosmic rays acceleration at SN1987A was extended to MeV photons. With the current upper limits on the pulsar luminosity in the supernova remnant the flux of >5 MeV photons will be well above the EGRET instrument sensitivity of GRO. A paper was published in Astrophysical Journal.

Another publication discusses the short duration (2 day) burst of TeV gamma-rays observed by the JAZOS collaboration. The scenario is that protons are accelerated at SN1987A in a pulsar wind shock with luminosity below the observational threshold. These protons are confined in the contact discontinuity, and their accumulated energy produce a superluminous gamma-ray burst when mixed with the ejecta by Rayleigh-Taylor instability.

(c) Pulsar binaries

Acceleration of particles is expected to occur in the standing shock created when a wind of relativistic electron-positron pairs (driven from the pulsar during spindown) impinges on the atmosphere of its companion.

Particle acceleration has been calculated, as well as the production of high energy gamma-rays when these fast particles collide with the atmosphere. Gamma rays above 100 MeV are predicted, and these should be by GRO.

(d) Accretion of a wind by a white dwarf

External non-thermal heating of a white dwarf corona occurs if it accretes wind from a companion. Our group has undertaken a detailed study of the most easily observed such system V471 Tauri: here, we know the external boundary conditions (wind from the K2 dwarf), and we have determined the inner boundary conditions from IUE spectra. This allows us to quantify for the first time how efficient the white dwarf is at protecting itself from the ravages of a passing wind. The efficiency is very high: only one part in 30,000 of the passing wind actually reaches the surface (Mu91). Presumably magnetic and/or rotational forces are protecting the white dwarf (as they protect the earth from the solar wind).

3. MHD turbulence.

Once structure is created in a stellar atmosphere on certain scales, further structure may be induced on other spatial scales by non-linear interactions. To describe these processes, we turn to turbulence theory, which is becoming of great interest in theories of coronal heating (Go90b).

(a) Turbulence in a magnetized atmosphere

Owing to the complexity of astrophysical plasma dynamics, application of MHD turbulence concepts to a variety of circumstances of interest requires that the local turbulence processes be modeled in some way, rather than computed exactly. Often this means that the existence of a cascade, perhaps driven by large scale gradients or instabilities, be assumed. In such cases a physically motivated choice of the cascade law may be important in deducing the nature and importance of turbulence in the system as a whole. In addition the local small scale (inertial range) turbulence may vary in its nature, especially in MHD where there are several types of energy containing fields and other "rugged invariants" (Fr75; Ma82) to consider, depending on the relative distribution of these quantities in the largest "eddies" or structures. Finally, the largest structures in an astrophysical plasma are also generally inhomogeneous, while most available theoretical insight is applicable to spatially homogeneous turbulence. Thus, the nature of the interaction between large scale inhomogeneities and local nearly homogeneous MHD turbulence is an important basic issue in these studies. Under the present NASA Theory Grant, we have made some progress in each of these areas.

(i) Phenomenology of inertial range turbulence. A crucial feature of the cascade is the inertial range spectral law, and the dependence on the energy transfer rate: the latter may be determined either by external parameters (for driven turbulence) or by the local nonlinear coupling strengths (for freely decaying turbulence). For quasi-steady MHD turbulence, two distinct spectral laws are quoted: $k^{-3/2}$ (Kr65) (often applied to MHD), and $k^{-5/3}$ (the Kolmogoroff law for hydrodynamically dominated flows). We have shown (Ma89) that the -3/2 and -5/3 laws may be viewed as opposite asymptotic limits of a unified spectral theory where the relaxation rate for triple correlations is the algebraic sum of contributions due to nonlinear effects and due to Alfven wave propagation. The ratio of large scale magnetic energy density in the large scale magnetic field to that of the inertial range fluctuations, controls the transition between the two spectral laws. This result is relevant in developing astrophysical MHD turbulence models in magnetic and non-magnetic parts of a corona: the slope of the spectrum determines the heating rate (Ho83).

(ii) Classification scheme for homogeneous 3D MHD turbulence. We have performed an extensive computational study of decaying 3D MHD turbulence (St90): behavior was classified according to insights gained from statistical mechanics, and from an extended energy principle, incorporating minimized energy, with conserved magnetic helicity and cross helicity. We found evidence for rapid relaxation toward rough equipartition between total fluctuating magnetic and kinetic energies, on a timescale of several to several tens of nonlinear times. For later times, we found a systematic tendency for relaxation towards states characterized by either selective decay, dynamic alignment or a balanced mixture of the two processes. In certain corners of the parameter space, the system can also relax along kinetic-magnetic energy equipartition trajectories, either with or without alignment. The results obtained should provide valuable guidance in assessing the distinct types of MHD turbulence, including greatly varying energy budgets and spectral characteristics, that can occur in astrophysical plasmas.

(iii) Transport of MHD turbulence in inhomogeneous large scale fields. WKB theory is often used to described propagation of wave packets in nonuniform but slowly varying background flows and large scale magnetic fields (Ho74). We have reconsidered this transport problem for turbulence, without assuming the validity of a wave dispersion relation, while also allowing for local modeled nonlinear couplings among the fluctuations. This has led to a formalism (Zh89,90) more general than WKB theory, which has been mainly applied so far to spatial evolution of solar wind turbulence. One interesting new feature of the theory is the appearance of linear couplings between local Alfven wave- like fluctuations that "propagate" in opposite directions. In particular, outward-type fluctuations are partially converted to inward type fluctuations rather rapidly (i.e., in leading, not higher, order) by interaction with the background gradients. This effect appears only in higher order in wave-WKB theory due to a non-resonant cancellation. Thus, if Alfven waves created by a star are heating the corona, inward flowing waves may also be created in the wind.

The evolution of coronal turbulence may also be strongly influenced by the backtransfer (to long wavelengths) of magnetic excitations induced by the presence of magnetic helicity. This may involve successive events of turbulent magnetic reconnection (Ma86a), possibly among discrete micro-plasmoids ejected from coronal heating sites (cf. Sect. 1 above). A simple model for observed 1/f low frequency spectra in the solar wind (Ma86b) invoked a coalescence scenario such as this.

(b) MHD turbulence in stellar winds

The presence of turbulence in stellar winds can be probed by test particle trajectories. Cosmic rays provide such particles as they struggle to reach the Earth's orbit from interstellar space. In our group, studies of propagation of cosmic ray particles has been developed to the point where it now provides a powerful technique for determining properties of MHD turbulence in the stellar wind in which we are immersed. In particular, a theoretical study shows how the correlation between magnetic field fluctuations and fluctuations in particle flux (the latter is in principle measurable) could serve as the basis for a powerful technique for studying turbulence and particle scattering processes in the wind. To study the 3-D structure of turbulence in the wind, one can compare the observed data with simulated data for three different turbulence models (slab, isotropic, and quasi-2-D). One component of the oparticle-field correlation is closely related to the Fokker planck coefficient for pitch-angle scattering: thus, we can estimate directly the scattering rates as functions of energy and pitch angle. Also, perpendicular scattering due to random walk of field lines appears as a second component of the particle-field correlation. This very surprising development really enhances the power of the method as a tool for studying mechanisms of particle scattering in MHD turbulence in winds.

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