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RESEARCH IN ASTROPHYSICAL PROCESSES

COOPERATIVE AGREEMENT NCC 5-37

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FINAL RESEARCH REPORT

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The following is a summary of the work completed under this Grant from 1986 through 1994.

1. Radiopulsar Turn-on and Evaporation of Companions in Very Low Mass X-ray Binaries and in Binary Radiopulsar Systems

A millisecond pulsar spun up in an accreting low-mass X-ray binary is expected to turn on suddenly when the mass accretion rate falls below a critical value near $10^{16} gs^{-1}$. The consequent energetic radiation from the pulsar would induce a wind from the companion and might even evaporate it. The secondary's evaporative wind would interact with the pulsar's Khz dipole radiation to form a bow shock and wake. These can effectively eclipse the radiopulsar microwave beam in either of two ways. For a very strong ionized wind, the bow shock and much of the wake plasma are overdense and reflect the pulsar beam. For a less dense wake/bowshock, plasma dispersion may smear the Khz modulation so that it is no longer detectible with present detectors. In either case a pulsar eclipse is recorded. A paper proposing that millisecond pulsars could evaporate very light companions was published by Ruderman, Shaham and Tavani. The subsequent discovery of PSR1957+20, a millisecond pulsar in an eclipsing orbit with a companion that has a strong wind, prompted an application of the model to this system by Kluzniak, Ruderman, Shaham and Tavani. Theoretical modelling of this remarkable system is leading to a much more detailed consideration of how MeV γ-rays induce winds, and how X-ray induced winds may be amplified by the increased metal abundances. These may be found in secondaries which were close to O-Ne-Mg dwarfs which accreted mass exceeding their Chandrasekhar limits, and became neutron stars.

2. Effects of Magnetospheric Pair Production on the Radiation from Gamma-Ray Pulsars

Mr.T. Zhu worked with Professor Ruderman on the interpretation of certain GRO observations of Gamma-Ray Pulsars. Mr. Zhu studied the expected strength of a gravitationally red-shifted pair annihilation line from the Crab pulsar. Here the annihilating pairs are presumed to be made by crossing γ-ray beams in the outer magnetosphere of the pulsar. These pairs flow down along "open" field lines to the region near the pulsar's polar caps where they annihilate. This process is not expected to be nearly as intense in the other known γ-ray pulsars where the γ-ray beam luminosity is less and the outer magnetosphere (where corotation needs near relativistic speeds) is further from the star. However, in Geminga-like γ-ray pulsars which seem to have a very large angle between stellar spin and magnetic dipole moment, large magnetospheric pair production can be sustained by γ-ray beams which pass through the inner magnetosphere where the local magnetic fields can greatly exceed 10^8 G. These pairs, produced on "closed" field lines, will all move toward the stellar surface. This circumstellar pair atmosphere affects observation of all surface X-ray emission in ways which depend upon magnetic field details. Mr. Zhu will next try to relate ROSAT X-ray results to GRO γ-ray data for such pulsars.

3. Radiation Transfer in the Atmosphere of An Illuminated Companion Star

The mechanism of wind formation in the outer atmosphere of a companion star illuminated by radiation from the primary requires a quantitative study of the heating and cooling processes occurring in the photospheric and coronal layers. Graduate student Marco Tavani, working with Professor Ruderman, performed a detailed calculation of the radiation transport of x-rays and soft γ-rays under several conditions realized in existing low-mass x-ray binaries. The radiation field in the atmosphere consists of two parts: (1) an external radiative flux which is incident on the atmosphere and is attenuated as it propagates inward; (2) a diffuse radiation field which is the result of reprocessing of the external flux by Compton scattering. The energy deposition and radiation transport depends on the ionization state of the atmosphere and it varies according to the characteristics of both the primary spectrum and of a possible high-temperature corona in the outer part of the atmosphere.

4. Evaporation of Millisecond Pulsar Companions

Mr. M. Banit, working with Professor J. Shaham, proposed a new mechanism for the formation of companion winds by radiation from the neutron star in Low-Mass X-Ray Binaries (LMXBs) and in Binary Millisecond Pulsars (BMPs). The mechanism is at work when radiation intensity is of the order of the Eddington intensity appropriate for the particular binary and the particular matter-radiation interaction process, and when radiation heat alone is unable to lift matter off the companion's surface with the necessary escape velocity. They found that a wind is then lifted off selective areas on the companion surface through the additional action of the radiation pressure on a slowly moving, relatively cool corona, fueled by the radiation heat.

The unusually large orbital angular momentum changes, with timescales as short as 10^7 years, that have been observed in several LMXBs and in the BMP 1957+20, can obtain when binary evolution in these systems is dominated by a sufficiently intense companion wind under the above circumstances.

A detailed hydrodynamical numerical code for analyzing wind motion of so complex a geometry is not yet available but is in the stage of being developed. To gain some physical insight, they nevertheless carried out a series of Monte Carlo simulations of free wind particles moving on ballistic trajectories.

The ballistic simulations are quite suggestive that under such conditions flows could torque the binary motion rather effectively. The fact that the wind flow is expected to reach supersonic velocities close to the companion lends credibility to their ballistic simulations for the torques. In particular, such wind patterns can naturally produce a decrease or an increase of the orbital period; its magnitude would be as large as the observed ones if the wind production efficiency is sufficiently high, with the companion bloated out of thermal equilibrium and close to its Roche lobe.

5. *Formation of Planets around Pulsars*

Wolszczan and Frail reported their timing measurements of the millisecond pulsar PRS1257+12. These measurements show pulse arrival-time delays that can be analysed in terms of at lest two stable modes of oscillations with a combined amplitude of about half the pulsation period.

It seems natural to attribute the pulse arrival-time delays to pulsar motion. The delays can be fit by assuming two planets in orbit around the pulsar. According to the fit, the masses correspond to $m \sin i$ values of $2.8 M_{\oplus}$ and $3.4 M_{\oplus}$ and periods of 98.2 and 66.6 days respectively. Here, m is a mass of a planet and i is the inclination angle of the orbital axis to the line of sight. Fitting the orbital parameters gives an upper bound on the eccentricities which is lower than 0.03 for each planet.

Banit, Ruderman, Shaham and Applegate suggested a new mechanism by which planets might form in such a way around a millisecond pulsar. According to this model, the formation of planets like those observed around PSR1257+12 occurs in a very late phase of low-mass X-ray binary or binary millisecond-pulsar evolution. They showed that the evaporation of the companion star in these phases can supply matter to a circumbinary "execretion" disk in which the physical conditions can allow the subsequent formation of planets, in circular orbits, around a millisecond pulsar.

6. Gamma Ray Bursts

The Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory (CGRO) has established that the distribution of gamma ray bursts (GRBs) is isotropic but bound in the radial direction. This finding suggests that GRBs are either cosmological and/or that they originate in an extended halo of our Milky Way Galaxy. The implied luminosities and the observed variability of the GRBs on time scales as short as one millisecond suggest that they originate on a compact object. We are currently investigating the possibility of creating GRBs from accretion flows onto black holes.

The mechanism of initial energy release in the form of a burst is not understood yet. Graduate student Mr. Ravi Pilla, together with Professor Jacob Shaham, is trying to find out the typical time scales involved in this energy release and the initial distribution of photons as a function of energy. It is very likely that a realistic model will have to include the effects of the spacetime geometry and the inhomogeneity in the photon density produced by the effects of gravity. However as a first step they formulated the problem in the Minkowski spacetime for a homogeneous and isotropic burst.

Quite independently of the above facts, galactic halo sources must involve the formation of opaque electron-positron-photon plasma which is generally known as a fireball, as is the case with the cosmological GRB sources. For these galactic halo models, observed rise times and luminosities imply that, if they are in thermal equilibrium (which is not the case, as is evident from the non-thermal nature of the spectrum), then they would be optically thick to Compton scattering (which dominates over the pair production opacity) with an average optical depth of a few hundred. But it seems very likely that initially we will have many more high energy photons compared to Planck distribution and in that case pair opacity can not be neglected.

For an arbitrary initial distribution of photons, Pilla formulated the equations of relativistic kinetic theory for non-equilibrium plasmas which can take into account various particle creation and annihilation processes (such as pair production and annihilation reactions and bremsstrahlung and double Compton scattering, etc.), various scattering processes and some Monte Carlo techniques, to compute various quantities of interest.

It is planned to first consider a homogeneous and isotropic non-equilibrium relativistic plasma which is confined to a sphere of a fixed radius R and has a given initial distribution of photons and particles which we characterize by some one-parameter family of functions. In the model, involving Kerr black holes, the initial photon distribution could arise from the Compton-Penrose process in the accreting plasma near the Kerr horizon. A baryon concentration N_b will also be included in the calculation. One defines a fictitious temperature T as the temperature of an equilibrium plasma which has the same energy density. Consider the range $25KeV \leq kT \leq 10MeV$ where k is the Boltzmann constant. This temperature range spans both galactic and cosmological GRBs. For such a plasma we study the equilibrating and radiative processes to estimate the relaxation and cooling time scales and the emergent spectrum. Pilla and Shaham are now set to study the influence of the baryon concentration on these quantities, to do a similar analysis for a freely expanding plasma to understand the interplay between the expansion time scale and the previous ones and obtain the emergent spectrum, to consider the effects due to curvature of the black hole and couple our initial conditions to those existing near accreting black holes.

7. Quasi-Periodic Oscillations in Low Mass X-ray Binaries

Current thinking on the origin of low magnetic field millisecond (m.s.) pulsars, thought to be neutron stars which rotate with these periods, puts them initially in low mass x-ray binaries. However, observational attempts to find such m.s. x-ray pulsars in LMXBs have so far failed. Instead, one observes in bright LMXBs quasi-periodic oscillations (QPOs). These were first discovered in the power spectrum of GX5-1.

Further observations have shown that the QPOs were a feature of the horizontal branch (HB), as well as of the other spectral branches, the normal branch (NB) and the flaring branch (FB). 5-8 Hz QPOs were observed in several sources on the NB.

While the origin of the QPOs on the HB seems to be magnetospheric, M. Banit (working with Professor J. Shaham) investigated a model for the 6 Hz QPO on the NB which is based on the dynamics of accretion far beyond the Alfven radius, where the magnetic field can actually be neglected.

The model proposes variations in optical depth which would cause luminosity variations via scattering and radiative transport. Such variations could come about via especially strong "sound" modes of a disk thickened by radiation pressure close to the Eddington luminosity. Monte Carlo simulations that he carried out showed that optical depth oscillations will cause oscillations in luminosity, much as in the spherical Lamb model, for very general oscillation geometries. These oscillations also exhibit a phase lag of hard photons over soft ones, as observed, if the electrons are hot, and show the right dependence of QPO amplitude and phase on photon energy.

Banit was able to prove generally that if accretion is strictly spherical, the process will not be consistent with a large-amplitude 6 Hz QPO as long as the hard photons lag behind the soft ones. The reason is that for the large optical depth needed to obtain a significant variation in intensity, hot electrons will be cooled down by the photons. Thus the 6 Hz process must be due to accretion disk dynamics rather than spherical accretion dynamics.

8. The Origin of High Mass X-ray Binaries, Runaway OB Stars, and the Lower Mass Cutoff for Core Collapse Supernovae

Graduate student James L. Terman developed a Monte-Carlo code for following the evolution of massive star binaries and studied the formation of massive X-ray binaries and runaway OB stars, which he assumed are single stars. The crucial difference between Terman's theory and the textbook picture is to drop the assumption of spherical symmetry in the supernova explosion, and include a distribution of asymmetric "kick velocities" inferred from the properties of radio pulsars. Terman finds that binaries which begin with small initial separations undergo non-conservation near transition, remain bound after the supernova explosion, and become high mass X-ray binaries. Binaries with larger initial separations undergo conservative mass transfer, are disrupted by the supernova, and produce an isolated radio pulsar and a single OB runaway. Thus, Terman explains the X-ray observations of both types of object, high mass X-ray binaries and OB runaways, with a single theory.

9. Dynamics of Planetary Atmospheres

Voyager imaging observations of zonal cloud-tracked winds on Neptune revealed a strongly subrotational equatorial jet approaching 500 m$\cdot$s^{-1}, with generally decreasing retrograde motion toward higher latitudes. Although its atmospheric composition, internal structure and rapid rotation are qualitatively similar to the other giant planets of the solar system, Neptune's predominantly easterly (retrograde) flow appears to represent a unique regime of planetary circulation. In a first attempt to understand Neptune's circulation, graduate student James Lumetta worked with Dr. Michael Allison of the Goddard Institute for Space Studies (and Adjunct Professor, Columbia University Department of Astronomy) on the development of a revealingly simple inertial model for the zonal motion based on the global homogenization of its potential vorticity.

The key assumption of the model is that the absolute (relative plus planetary) vorticity for an upper moving "weather" layer varies in direct proportion to its effective thickness, which in turn slopes downward with increasing latitude in proportion to the Coriolis acceleration of the zonal motion. (Similar models have been previously applied to the western boundary layers and equatorial undercurrents of the ocean.) Away from the equator, the absolute vorticity is dominated by the planetary vorticity, so that the thickness varies roughly in proportion to the sine of the latitude. Steady gradient flow balance in turn implies an increase in the retrograde zonal velocity from high to low latitudes. The inferred correlation of faster motion with effectively "thinner" flow is analogous to the intensification and rising thermocline of the gulf stream toward its westward boundary. Allison and Lumetta constructed numerical solutions to the inertial Neptune model posed as a nonlinear boundary value problem, confirming to good approximation the results of a simple analytic solution. The prescribed model flow profile relates the equatorial velocity to the mid-latitude shear, in good agreement with the Voyager data, and implies a global horizontal deformation scale of about 3000 km. A modified piecewise-constant potential vorticity model can be fitted to a prograde polar jet on Neptune, without substantial alteration of the predominantly retrograde flow at sub-polar latitudes. The results of this study should be amenable to independent test by the further analysis of Voyager imaging observations of the spatial-temporal behavior of vortices and waves.

10. Two-Point Closure Modeling of Stationary, Forced Turbulence

In order to test a two-point closure model of stationary, forced, isotropic, homogeneous, incompressible turbulence, a numerical code was developed by Oleg Schilling (working with Dr. V. Canuto) that is based on the eddy-damped, quasi-normal Markovian model to treat the nonlinear interactions described by the Navier-Stokes equations. The results of the computations were successfuly tested against two important representative flows—laboratory thermal convections and channel flow. In addition, the solution of the linear stability problem for compressible convection was completed: the growth rate resulting from this solution will subsequently be used in a turbulence model for compressible convection.

11. Models for the General Circulation of Saturn

Most recent theories for the rapidly rotating Jovian dynamical systems begin with the extreme assumption of either a deep cylindrical flow configuration, extending on cylinders of motion (co-axial with the planetary spin axis) throughout the molecular hydrogen envelope of the planetary interior, or else a shallow thermal wind layer supported by strong gradients in density and temperature, confined to a depth of a few scale heights. Both pictures have thus far failed to provide a satisfactory account of all features of the Voyager wind and temperature observations. Both types of theory require as a starting point some additional assumptions about the buoyancy contrast, eddy fluxes, and boundary conditions for atmospheric levels thus far inaccessible to observation. Although the diagnostic analysis of Voyager imaging, infrared and radio occultation measurements has provided useful constraints on the models, the data are not yet sufficient to admit a unique inference of the basic flow kinematics.

We proposed a new conceptual model for the zonal circulation of Jovian atmospheres, with particular emphasis on Saturn, based upon the assumption that the convectively unstable Jovian atmospheres attain an *ad hoc* multi-layer potential temperature distribution which extends, vertically, deep into the molecular hydrogen envelope. Under the assumptions of potential vorticity conservation, and self-similar structure in the vertical co-ordinate (from layer to layer) the equations governing the fluid motions of the uppermost (observable) layer reduce to those of a negative reduced gravity shallow water system identical to the convectively layered latitudinally variable thermocline of Allison and Lumetta (1989). While based on a convectively unstable, *ad hoc* potential temperature field, the model provides an account of both the high latitude jet streams, and the equatorial intensification of the prograde flow, with the model Saturn flows being stronger and more generally prograde than model Jupiter flows, consistent with the Voyager cloud-tracked wind observations of these two planets. Numerical solutions to the axi-symmetric model equations bear a remarkable resemblance to the observed Saturn wind profile.

12. Compressible Convection in Stellar Interiors

In most stellar interiors, the transport of heat occurs by turbulent convection. Consequently, all stellar structure theories require an expression for the turbulent convective flux Φ_c. The lack of a general theory of turbulent convection that could be readily implemented in astrophysical problems prompted the use of the mixing length theory to provide an expression for Φ_c, whose general validity is difficult to assess, and its extension to include rotation, magnetic fields and other phenomena present in stars is ambiguous. As a result, stellar structure models that rely on mixing length theories cannot be fully predictive.

To incorporate the effects of fully-developed turbulence, as well as compressibility, in stellar convection, Oleg Schilling (working with Dr. V. Canuto) developed a model in which a fully deductive, two-point spectral closure theory of turbulence–the direct interaction approximation–is used to model the nonlinear interactions in the Navier-Stokes equations, and the energy input required to sustain the turbulence is modeled via a source function derived from the associated linear stability problem for compressible convection. The stability problem has been solved for the source function, and the turbulence model equations for compressible convection have been derived and coded numerically.

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