FINAL TECHNICAL REPORT FOR NASA AWARD NAG5-7011: THEORETICAL STUDIES OF ACCRETING NEUTRON STARS

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I. Introduction

Among the newly discovered classes of X-ray sources which have attracted wide attention are close binary systems in which mass is transferred via Roche lobe overflow from a low mass donor star to its neutron star companion. Many of these sources exhibit intense bursts of X-ray radiation as well as periodic and quasi-periodic phenomena. Intensive analysis of these sources as a class has provided insight into the accretion process in binary star systems and into the magnetic field, rotational, and nuclear evolution of the underlying neutron star. In this proposal we have focused on theoretical studies of the hydrodynamical and nuclear processes that take place on the surface of accreting neutron stars in these systems. The investigation of these processes is critical for providing an understanding of a number of outstanding problems related to their transient behavior and evolution.

II. Summary of Scientific Results

1. Nuclear Processing in Accreting Neutron Stars

There is a widespread consensus that thermonuclear flashes in the surface layers of accreting neutron stars are responsible for the Type I X-ray burst phenomenon. The model successfully reproduces the energetics of the observed bursts ($\sim 10^{38} - 10^{39}$ ergs), their timescales (rise time $\sim$ several seconds; burst duration $\sim 10 - 100$ s; recurrence time $\sim$ several hrs), and the spectral softening seen during burst decay. This success has provided the strongest theoretical evidence that neutron stars are involved in the X-ray burst phenomenon. Although the general properties of X-ray bursts can be adequately described by the thermonuclear flash model, discrepancies exist between the predictions of the thermonuclear flash model and observations. In this proposal we have focused on the irregular burst behavior (or complete lack of bursts) for very bright sources. For example, the sources GX 17+2 and Cyg X-2 reveal standard Type I X-ray bursts, however, the equally bright sources Sco X-1, GX 5-1, and GX 340-0 have not been seen to exhibit such behavior. These observations suggest that either mass accretion rate variations on timescales of minutes mask these nuclear-powered luminosity fluctuations or that the physical conditions under which nuclear burning takes place may be modified. We have explored the consequences of spatial dimensionality in the problem and have performed numerical calculations in which the assumption of spherical symmetry and steady state flame fronts has been relaxed. The results of multi-dimensional burning in the accreted hydrogen-rich envelope show that i) peak burning is nearly uniform over the region on the neutron star surface where the column accretion rate is spatially constant, and that ii) bursting behavior is not periodic. The diffusion of heat in the lateral direction smooths out the temperature perturbation, leading to a spatially uniform (in the lateral direction) thermal evolution to peak temperatures in the accreted layer. This is in contrast to the case for the accretion of helium-rich matter where narrow burning fronts were found to ignite the gas ahead of the ignition region. It is inaccurate to describe the present cases in terms of narrow fronts since the steady state flame width, $\delta \gtrsim 10^4$ cm, is significantly greater than the scale height of the envelope, $\lesssim$ 300 cm. The significant difference between these length scales is a consequence of the high temperature ($\gtrsim 3 \times 10^8$ K), which results in low helium abundances ($Y < 0.1$) in the burning regions. On the other hand, for column accretion rates $< 10^4$ g cm^{-2} s^{-1} convective energy transport is found to be important in one-dimensional models, making it possible that a flame front will develop and propagate in the lateral direction. We note that the actual column accretion rate limit may be modified when the full two-dimensional effects are included. The numerical results suggest that fuel pooled on the neutron star surface is expected to burn as a unit in the high accretion rate regime. Hence, observable X-ray bursts would occur only if the matter spreads over the entire surface.

To investigate the composition of the deep interior layers of neutron stars which undergo X-ray bursts, time dependent accretion studies are being carried out for a range of mass accretion rates where the accreted envelope is thermally unstable. In contrast to previous studies of the deep interior layers, a steady state approximation was not adopted. In our investigation, we make use of a more extensive nuclear reaction network, including the most recent nuclear cross section data and newly calculated electron capture cross sections for very heavy nuclei. The importance of these studies is two-fold. First, it is necessary for determining the viability of the photodisintegration trigger for the nuclear energy release of super bursts, recently discovered from the Rossi X-ray Timing Explorer (which last more than 1000 times longer and emits more than 1000 times the energy of normal X-ray bursts), since the results depend very sensitively on the assumed heavy element composition and isotopic abundances. Secondly, since the neutron star crust contains less than 0.1 $M_\odot$, it has long been recognized that the neutron star crust can be replaced several times during the neutron star's lifetime in a low mass X-ray binary system. As a result, the thermal and electrical properties of the crust are a likely to be a function of the evolution of the system and to depend on the rate of mass accretion. Since these properties significantly differ from their properties during its nascent state, it is likely that the magnetic field of neutron stars at a given rotational period and luminosity depends on its previous thermal evolution. Making use of our results of the nuclear processing in the outer envelope layers we are calculating the compositional changes in the deep subsurface layers due to electron captures onto nuclei (neglected in previous studies) at intermediate densities and the neutronization of the matter at high densities. These studies are necessary for determining the degree of impurities in the neutron star crust and, consequently, its conductivity and, therefore, are important input for studies describing the evolution of the magnetic field strength and its topolgy in accreting neutron stars in binary X-ray sources.

2. Hydrodynamical Processes on Accreting Neutron Stars

In a preliminary study, we have carried out a series of one dimensional time dependent hydrodynamical calculations to explore the conditions under which the accretion of hydrogen-rich matter can lead to localized burning on the surface of a neutron star. The preliminary results of a calculation in which thermal inhomogeneities are present suggest that gas flow due to a baroclinic instability can develop on the neutron star surface. The departure from barotropy (baroclinicity) results in flows which cause matter to spread. If the spreading occurs over a sufficient extent of the neutron star surface, this effect may be key in understanding the diversity of observed bursting activity seen in the bright low mass X-ray binaries. In this picture, the spreading is more effective where irregular bursting behavior has been seen and less effective where no bursting activity has been observed.

To follow up on these results, two dimensional time dependent hydrodynamical calculations have been undertaken to assess the importance of these flows and to delineate the mass accretion rates and magnetic field regimes where such spreading is effective. Preliminary results indicate that hydrodynamical effects dominate the evolution and suggest that the burning front propagates at speeds significantly greater (by more than a factor of 1000) than that found for thermal diffusion operating alone. However, the time scale over which the computations could be carried out was limited due to the severe time step restriction imposed by acoustic waves on the numerical solution. Hence, in order to determine if the burning front spreads or is quenched over a sufficient extent of the neutron star surface, a new numerical method for computing hydrodynamic gas flows has been developed. Our method which filters out sound waves permits the flow to be computed without the restriction imposed on traditional hydrodynamical methods. Since the hydrodynamic field is nearly in hydrostatic equilibrium with strong vertical stratification, we have expanded the solution about this equilibrium with deviations from the hydrostatic pressure neglected in the equation of state and the energy equation. In this manner, sound waves are filtered out and timesteps can be based on the vastly slower convective motions induced by nuclear burning and gravity. This can be justified by an expansion in terms of the Mach number, the ratio of a characteristic convection or flame velocity to the sound speed, which is often very small (< 0.01) for our application.

This low Mach number model differs from a related model, the anelastic model, in which the density fluctuations are neglected in the continuity equation so that the resulting velocity field is also essentially incompressible. However, the anelastic method is based on the assumptions that lateral variations are small, conditions which are not generally met in burning fronts. This low Mach number method allows us to numerically simulate subsonic flows over more relevant time scales and, hence, reduce the dependence of the results on initial conditions. Central to the method is the solution of an elliptic equation of variable coefficients for the pressure perturbation (i.e., the departure from hydrostatic equilibrium). A numerical code based on this method has been written for a parallel computing architecture. The method has a wide range of applicability to a variety of astrophysical problems, and we are applying it to investigations relevant to our proposed studies of baroclinic instabilities and of the interaction of nuclear burning with convection on the surfaces of accreting neutron stars.

III. Publications

On Self-Ignition and the Propagation of Flame Fronts on the Surfaces of Accreting Neutron Stars, A. Bayliss, E. Sandquist, and Ronald E. Taam 1998, BAAS, 30, 1310

Multi-dimensional Burning in the Surface of Accreting Neutron Stars, Ronald E. Taam, Alvin Bayliss, and Eric Sandquist 1999, BAAS, 31, 1510

Irregular Bursting Activity in Bright Low Mass X-ray Binary Systems, Ronald E. Taam, Alvin Bayliss, and Eric L. Sandquist, submitted to ApJ

Hydrodynamical Flows on Accreting Neutron Stars, David Lin, Alvin Bayliss, and Ronald E. Taam, in preparation

Nuclear Processing and Impurity Concentrations in Accreting Neutron Stars, F. Sutaria, A. Ray, J. Pruet, R. Hoffman, and R. E. Taam, in preparation