Statement of Research

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If I am only allowed one sentence to describe my future career, it is: I wish to be a computational astrophysicist.

My interests in computational astrophysics and numerical simulations stem from 1995 when I began to work as a mission analyst engineer in Beijing Institute of Spacecraft System Engineering, China. My major work was to model the orbital dynamics of a man-made satellite around the Earth using the perturbed two-body problem, which takes into account of the perturbation correction to the Earth's potential field caused by its non-spherical shape. I independently developed a code that made use of the Runge-Kutta method to integrate the equation of motion of the satellite, calculated its orbital motion and solar eclipse time after launch and optimized the scenario of orbital maneuvers to achieve minimum fuel consumption. This code was used to perform the primary mission analysis tasks for some of China's Geo-Synchronous communication satellites. That was my first experience in solving physical and engineering problems using numerical techniques. But the story did not end there. As my desire of pursuing a Ph.D became stronger and stronger, I decided to come to the United States, which boasts the best research in Astronomy and Astrophysics around the world.

In 1999, I started my five-year Ph.D. journey on the beautiful campus of Louisiana State University in Baton Rouge, where Dr Joel Tohline, who became my thesis advisor, directed me to a totally new field: full 3D computational hydrodynamics. My Ph.D. research concentrates on 3D numerical simulations of various astrophysical systems. In the past three years, I have utilized the state-of-the-art computational hydrodynamics tools developed by the LSU astrophysics group to study several astrophysical problems listed below:

(1) The nonlinear development of the gravitational-radiation-induced secular bar-mode instability in rapidly rotating neutron stars. This classical instability was first discovered by Chandrasekhar and was believed to give birth to a special kind of bar-like configuration, the Dedekind ellipsoid, which has large internal rotation yet maintains a stationary bar shape as viewed from the inertial frame. We successfully modelled the nonlinear development of the bar-mode instability and calculated the gravitational waves that are potentially detectable by LIGO. We also found that the final Dedekind-like configuration is hydrodynamically unstable to high order turbulence due to its highly differential rotation. Our results suggest that it is unlikely that Dedekind-like objects exist in the universe. This project was carried out in collaboration with Lee Lindblom from Caltech and has been developed into my doctoral dissertation.

(2) 3D simulations of the core collapse of a massive star. A supernova explosion is one of the most spectacular events in our universe, yet is still not well understood. As one of the many efforts that are being undertaken to understand the physics behind supernova explosions, we made use of LSU's hydrodynamics code to extend the work of Ott et al. (2004, ApJ, 600, 834), who performed a set of 2D simulations on the core collapse of progenitor models from Woosley and Weaver (1995, ApJS, 101, 181) with some differential rotation law applied. By using a simple description of the system's equation of state (two polytropes of different polytropic indices), our 3D simulations of the free-fall core collapse yielded similar results to that of Ott's 2D code and even followed the post-bounce evolution of the core for many dynamical times. However, at late times, our 3D simulation showed that an m=1 spiral mode developed and transported angular momentum outward, therefore the central core underwent a second but mild collapse. This complements the suggestion of New et al. (2001, ApJ, 550, L193) that for a centrifugally hung core, if the m=1 spiral modes develops, it can cause the core to collapse to nuclear density. The paper for this project is in

preparation.

(3) The plausibility of the birth of close binary systems via rotational fission mechanism. In this project, we modelled the evolution of a rapidly rotating proto-stellar cloud that initially has a Maclaurin-like configuration and is dynamically unstable to the m=2 bar-mode. After the model settled down into a steady bar-like configuration, we introduced some simple cooling mechanism to cool the system. As a result, the bar shrank and began to spin up, and finally was oscillating between a bar-like configuration with one central density maximum and a dumbbell shape that has two off-center density maximum. But since the system had a lot of excess angular momentum (compared to a close binary system with similar mass and size), fission did not happen in the computing time allowed by our current computational power. The paper for this project is also in preparation.

In addition to studying specific astrophysical problems of interest, I have been involved in designing and implementing different numerical schemes and techniques to solve different physical equations such as Navier-Stokes Equation and Poisson's Equation. I also gained some knowledge on the relativistic hydrodynamics after taking the 2003 International Graduate Summer School in Computational Hydrodynamics jointly hosted by Penn State University and University of British Columbia.

The tools that are critical to my Ph.D. research include large scale parallel computing and 3D visualization because the computations and data required by a full 3D simulation are much larger than that needed in an ordinary orbital dynamical calculation. In order to gain a better understanding of these tools, I have completed a second Master's Degree in LSU's Department of Computer Science. In the past three years, I became familiar with high performance computing, code optimization, different visualization tools such as OPENGL and Maya, gained some experience on grid computing from the numerical relativity group led by Ed Seidel and Gabrielle Allen, a group that has recently moved from Albert Einstein Institute in Germany to LSU. I also completed some projects and gained some experience in Monte Carlo method and molecular dynamics when taking the computational physics course taught by Rajiv Kalia, who now is a professor in University of Southern California.

While working with computational physicists and computer scientists for years, I have been completely caught by this interdisciplinary field of astrophysics and computer science. I really would like to extend my future research to study other interesting and complicated astrophysical phenomena such as supernova science, numerical relativity, gravitational wave astronomy, and gamma-ray bursts, all of which generally require high performance scientific computing and various numerical techniques such as adaptive mesh refinement. If possible, I would like to investigate the following problems:

(1) Incorporating full 3D hydrodynamics code with all the proper micro-physics to study the core collapse of massive stars. Our work on core collapse with Ott and Burrows used a very simple description of the equation of state of the system, which is not sufficient to describe the realistic situation. In order to gain a better understanding, it is necessary to use a more realistic equation of state that takes into account of micro-physics such as degenerate electron gas, neutrino transport, etc.

(2) The stability criterion for different bar-like configurations. In the past research, we have been able to construct two bar-like configurations from secular and dynamical bar-mode instabilities of rapidly rotating stars, both of which have large internal flows. One of them, which forms from the dynamical instability and is more close to Jacobi-like ellipsoid, exists for a long time; yet the other one (the Dedekind-like ellipsoid forming from the gravitational-radiation-induced secular instability) is dynamically unstable to high order turbulence. It would be very interesting to explore the criterion that governs the stability discrepancy of these two kinds of bars that are similar to each other in many ways. It is also important to determine the growth rate of the high order turbulence in the Dedekind-like ellipsoid because it may limit the maximum amplitude of the secular bar-mode and influence the detectability of gravitational waves from this instability.

(3) High order secular instability in rapidly rotating neutron stars. As appreciated by linear theory

and our numerical study, the $m = 2$ secular bar-mode instability has a very long growth time when the rotating neutron star just passes its critical limit where $\beta \equiv T/|W| \approx 0.14$, (where T is the rotational energy of the star and W is the gravitational energy of the star), because its frequency just passes zero and the strength of the gravitational radiation-reaction force is proportional to its frequency raised to the fifth power. However, the critical limit of the $m = 3$ mode has a lower β value, the frequency of the $m = 3$ mode is much higher than that of the $m = 2$ mode when $\beta \approx 0.14$, so its growth rate is much shorter. Therefore the $m = 3$ mode may be dominant in this range of β. This may change the detectability of the gravitational waves from rotating neutron stars, and also influence the maximum spin frequency a rigidly rotating neutron star can reach because the $m = 3$ secular instability sets in at a lower β value than that of the $m = 2$ mode.

(4)What is the outcome of the secular bar-mode instability when it arises in *differentially rotating* neutron stars? Our previous investigation of the secular bar-mode was confined to rigidly rotating neutron stars, yet neutron stars may be born differentially rotating, so it is important to study the secular bar-mode instability in differentially rotating neutron stars. According to perturbation analysis by Imamura et al. (1995, ApJ, 444, 363), the critical limit of the secular bar-mode is reduced to $\beta \approx 0.09$ in some extremely differentially rotating case. Shibata et al. (2003, MNRAS,334, L27), New et al. (2001, ApJ, 550, L193) also reported discoveries of dynamical instability in differentially rotating systems at much lower β values than traditional limit of $\beta \approx 0.27$, so differential rotation may play a very important and different role.