RESEARCH and TEACHING

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Research

My research centers on theoretical study of compact objects (neutron stars and black holes, pulsars), radiative processes (radiative transfer, stellar atmospheres, effects of strong magnetic fields), astrophysical fluid dynamics and MHD (accretion disks, density waves, binaries, stellar oscillations, gravitational collapse), gravitational waves, atomic physics and condensed matter in astrophysics, neutrino astrophysics and related subjects.

In this section the notation [pub 1] means "publication 1 on the attached publication list".

I. Highlights of Research Accomplishments

I have written 92 papers (73 refereed) that cover several different areas of theoretical astrophysics. The most significant are summarized below.

1. Radiative Transfer in Strong Magnetic Fields: Since 2001, I have devoted significant effort on the subject of radiative transfer in the atmospheres of highly magnetized neutron stars (NSs). With graduate students, we elucidated the novel physical effect of vacuum polarization (an effect of strong-field quantum electrodynamics) on radiative transfer in highly magnetized plasmas [pub 50,57]. We showed that vacuum polarization induces "resonant mode conversion", in which X-ray photons change from one polarization mode into another (this is analogous to the MSW mechanism of neutrino oscillation), and this can significantly affect the radiation spectrum from highly magnetized NSs (e.g. soften the hard spectral tail due to the nongrey atmospheric opacities and suppress the width of absorption lines). Quantitative atmosphere models incorporating these vacuum resonance effects have been developed [pub 56,82]. These vacuum polarization effects may explain the spectral properties of quiescent magnetars as well as recent spectral line observations of isolated NSs. Even for modest field strengths ($B \lesssim 10^{13}$ G), we found that vacuum polarization can still leave a unique imprint on the X-ray polarization signal [pub 59]. With A. Potekhin and graduate students, we have studied the equation of state, polarizibility tensor and opacities of magnetic, partially ionized H plasmas, and have constructed the first NS atmosphere models that include self-consistent treatment of the thermodynamics and opacities of bound H atoms in strong magnetic fields [pub 61,65,72]. Motivated by recent laboratory experiments, we recently considered how the property of axions can be constrained from observations of magnetic NSs [pub 83].

2. Dynamics of Accretion Disks: In 1999, I studied several new physical effects associated with disk accretion onto magnetized stars (neutron stars, white dwarfs or pre-main-sequence stars) [pub 35]: Under quite general conditions, the inner region of the disk can experience magnetic forces and torques which induce warping, precession and resonances in the disk. With graduate students we have studied global warping/precession modes in magnetic disks [pub 48,49,63]. These effects (largely overlooked by previous researchers) can potentially play an important role in explaining a number of observational puzzles (e.g., quasi-periodic variabilities in X-ray binaries, CVs and T Tauri stars). In 2003 I further suggested that similar magnetic effects may operate in black hole accretion disks threaded by large-scale magnetic fields and these may provide an explanation for the jet procession observed in a number of systems [pub 60]. Two recent works on disks include a study of resonant wave excitations in 3D disks by an external periodic forcing (this generalizes the classical work by Goldreich & Tremaine) [pub 75,91] and an explicit calculation of the corotation amplifier in disks taking into account of the corotation singularity [pub 92].

3. Matter in Strong Magnetic Fields: I have a longstanding interest in the atomic physics and condensed matter physics in strong magnetic fields ($10^{10} \lesssim B \lesssim 10^{15}$ G) [pub 44]. For example, we were the first to quantify the binding mechanisms of small H_n molecules ($n = 2, 3, \cdots$) and chains (discussed qualitatively by M. Ruderman in 1970's) and to obtain reliable binding energies. We also studied the phase diagram of the hydrogen-helium surfaces of strongly magnetized neutron stars [pub 26,44]. Recently, with graduate student Z. Medin we have completed a detailed ab initio calculation (using a new density-functional theory code, developed over three years) of the cohesive properties of condensed matter (H, He,C and Fe) for a wide range of magnetic fields relevant for pulsars and magnetars [pub 80,81]. These quantities are of fundamental importance for neutron star surfaces, and have implications for surface (thermal) emission and particle acceleration near polar caps [pub 89]. With A. Potekhin we have also studied the radiative properties of partially ionized magnetic plasmas [pub 65] and the physics of ion cyclotron lines [pub 86].

4. Sources of Gravitational Waves: I have studied the gravitational waves produced by rapidly rotating, nascent neutron stars undergoing gravitational radiation driven bar-mode instability [pub 15]. While the basic physics underlying this instability was understood in the 1970's by S. Chandrasekhar and associates, we were the first to realize that such bar-mode can produce unique gravitational wave signals, and that the waveforms can be calculated exactly (for incompressible fluid) using a semi-analytical method that we developed. This is the only exact solution (albeit under idealized conditions) for the nonlinear evolution of the so-called Chandrasekhar-Friedman-Schutz (CFS) instabilities, and represents an efficient mechanism of gravitational wave generation from proto-neutron stars. My Ph.D. thesis work (completed in 1994) developed a semi-analytical method to study hydrodynamical processes in coalescing neutron star binaries, and uncovered a tidal instability which can accelerate binary coalescence at small orbital separations. I was the first to show that tidal effect stabilizes the neutron star against collapse [pub 22], a result confirmed by many later studies. I have studied the resonance effect in coalescing binaries [pub 13,34,78] as well as tidal interaction in Kerr metric [pub 37]. I have also examined the magnetic field effect on r-mode oscillations in young neutron stars [pub 42].

5. Gravitational Collapse and Neutron Star Kicks: One of the interesting puzzles in supernova research concerns the origin of neutron star velocities and supernova asymmetry. I have studied several physical mechanisms of neutron star kicks, including hydrodynamically driven, neutrino-magnetic field driven and electromagnetically driven kicks. With P. Goldreich we studied the growth of asymmetric perturbation during core collapse [pub 38]. As a by-product, I carried out a detailed analysis of the stability properties of a large class of self-similar solutions that characterize gravitational collapse and accretion in both supernova and star formation contexts; a potentially important finding is that for sufficiently soft equation of state (e.g., isothermal), there exists a global bar mode which grows during collapse [pub 39]. With Y.-Z. Qian and former Cornell graduate student P. Arras, I have carried out detailed studies of neutrino transport in strong magnetic fields to determine whether asymmetric neutrino emission may give rise to sufficient neutron star kicks [pub 28, 30, 31, 32]. With J. Cordes and D. Chernoff, I examined the electromagnetic "rocket" effect due to off-centered magnetic dipole radiation from pulsars and considered the effect of gravitational radiation on kicks [pub 43]. Recently, with graduate student C. Wang of NAOC, we found a correlation between pulsar velocity and the spin direction (based on radio polarization data) [pub 70]; this provides useful constraints on possible kick mechanisms and initial conditions of proto-neutron stars [pub 84].

6. Dynamical Tides and Lensing in Binary Pulsars: In 1995-1997, I was the first to consider various hydrodynamical effects (spin-orbit coupling and dynamical tides) that proved to be important in determining the puzzling orbital behaviors of a new class of binary pulsars with main-sequence star companion [pub 18, 23, 27]. Precise pulsar timing has allowed for exquisite measurement of these hydrodynamical effects. Since then, some of the hydrodynamical effects have been incorporated into the standard pulsar search/analysis program. On the theoretical side, the key insight was the realization that retrograde stellar rotation can significantly enhance the strength of dynamical tide by shifting tidal resonances with the stellar oscillation modes. With R. Rafikov, we studied the timing signature of gravitational lensing (e.g. modified Shapiro delay) in the double pulsar system J0737-3039 [pub 66]. Although recent timing observation showed that the binary orbit is not as edge-on as early observation indicated, therefore making the lensing effect unobservable, our new analytical formulae for the related effects (e.g. aberration, pulse dilation) may be useful for other systems (including pulsar/black hole binaries) [pub 74,76].

II. Current/Planned Research

It is difficult to predict my research more than a few years in advance. In the following I will describe some of my ongoing research or projects that I have recently started.

1. Magnetic Neutron Stars: I will continue to work on various aspects of the physics of highly magnetized neutron stars as observations continue to bring surprises. I am interested in understanding the relationship/links between various manifestations of neutron stars, including radio pulsars, radio transients, magnetars, thermal emitters, and compact central objects in SNRs. Recent observations revealed strong evidence for ion cyclotron emission lines during magnetar outbursts. The nature of spectral lines recently observed from a number of isolated NSs remains uncertain. Thus more theoretical work on partially ionized magnetized plasmas and ion cyclotron line formation is needed. Our recent calculations show that for sufficiently strong magnetic fields, the neutron star surface may be in a condensed state. We are interested in understanding the implications of such surface condensation for thermal emission and magnetosphere processes. The difference between magnetars and high-B radio pulsars is of great interest as both have similar inferred magnetic field strengths but have very different radiative properties. With graduate students, we are modeling pair cascade processes in the superstrong magnetic field regime; these have a number of novel features that are absent in the "normal" ($\sim 10^{12}$ G) field regime (e.g., synchrotron emission is inefficient as one-photon pair production never produces electron/positron in high Landau levels). We will be interested in studying gamma-ray emission from the inner magnetosphere of pulsars and magnetars, in anticipation of new data from GLAST. We have recently studied wave modes in the magnetospheres of high-B pulsars/magnetars, and we are now investigating the propagation of radio waves in such magnetospheres.

2. Disks and Accretion Flows: Accretion flows are ubiquitous in astrophysics, and I expect to work on several aspects of disk theory in various astrophysical contexts. Here I give two examples: **(1) Disk instabilities and QPOs.** Observations over the last decade have revealed a variety of quasi-periodic flux variabilities in accreting neutron star and accreting black hole systems (including supermassive black holes and intermediate-mass black holes). The phenomenology is well established, but there is a lack of concrete theoretical models. Global, overstable disk oscillation modes provide a possible explanation. With graduate students, we are examining the connection between super-reflection/corotation amplifier, corotation resonance, Rossby waves and global instabilities in accretion disks/tori [pub 92]. General relativistic effect (which naturally induces a maximum in the specific vorticity profile) will be included. We will calculate global linear modes (with various flow boundary conditions) and study their observational manifestations. Nonlinear saturation at corotation will be studied numerically. We are also interested in understanding how magnetic fields (both sub-thermal and super-thermal) affect these global modes. **(2) Disk-planet interaction.** We recently developed a general theory for the excitation of waves in 3D gaseous disks with finite thickness by a rotating external potential (e.g., an orbiting planet or satellite) or a generic forcing [pub 75,91]. This work extends the well-known study by Goldreich and Tremaine (for 2D disks), and allows for 3D bending waves (and g-modes) to be treated self-consistently. It was found that under some conditions, vertical resonances are an important channel of angular momentum transfer between the disk and the external potential. We are now studying the dynamical evolution of a circumstellar disk perturbed by a planet in an inclined orbit due to wave excitations.

3. Sources of Gravitational Waves: With the initial LIGO completed and the improvement in LIGO sensitivity expected in a few years, as well future prospect for LISA, it is likely that I will devote some effort to study the astrophysics of gravitational wave sources (a subject that I have worked on actively in the past, but not in the last few years). One problem I am interested in concerns the formation for black hole - neutron star binaries, since different models give very different event rates for black hole – neutron star binary coalescence for the enhanced LIGO (mLIGO). This would involve understanding accretion and mass ejection of neutron star in the common envelope phase of binary evolution. I am interested in studying several theoretical issues related to gravitational radiation driven instability in rapidly rotating proto-neutron stars, including the effect of bulk viscosity (due to nonequilibrium neutrino emission), the interaction between a growing bar-mode and a surrounding disk, and the nonlinear development of secular bar-mode instability – these (secular) effects are difficult to study using numerical simulations because of the long timescale involved. Another problem concerns resonant tidal interactions in ultracompact white dwarf binaries and how these may be probed by LISA. Finally, the warping, precession and realignment of accretion disks in merging supermassive black hole binaries is a topic I have started working on recently.

4. Other Topics: (1) Bubble dynamics in Clusters: I have been working on the dynamics of AGN driven bubbles in clusters of galaxies. A semi-analytical model describing the expansion (from ultra-relativistic to non-relativistic) and rising (due to buoyancy) of bubbles in the ICM has been developed. I am interesting in studying the stability of the bubble and the effect of magnetic fields. These are relevant to understanding the heating mechanisms of ICM. **(2) Galactic magnetic fields:** With JinLin Han (NAOC, Beijing), I am studying how to extract information of Galactic magnetic fields (e.g. small-scale inhomogeneity, power spectrum) from current and future radio surveys (e.g. synchrotron intensity and polarization map, Faraday rotation survey of pulsars).

Teaching and Advising

I. Course Teaching

Since 1997 I have taught nine different courses. I have thoroughly enjoyed my teaching experience. I believe that research and teaching are mutually beneficial: Students are always excited and motivated to learn about current research topics related to the course material; on the other hand, teaching different courses has given me a better appreciation of different areas of astronomy. I have found that before I can teach a course, I always have to develop the course material by myself from scratch and think through my way of presenting it. Therefore teaching each of the courses has been a new, rewarding experience for me. In my teaching, I tried to challenge the best students in the class, while making sure that the majority of the students can master the basic material. I have devoted a considerable effort into the pedagogy for each course (this is particularly important when new physics concepts or methods are introduced — my approach has always been to make sure that the students develop an intuitive feeling on the subject under study).

Astro 211: Stars, Galaxies and Cosmology. This course introduces science and engineering freshman/sophomore students to major topics in modern astronomy. The course emphasizes explanations, not only descriptions, of astronomical facts/phenomena. Many major topics from stars to cosmology are covered. The students are introduced to many new (for them) physics concepts and tools and learn how to use physics to understand modern astronomy (e.g., Doppler effect and Kepler problem are discussed quantitatively and used to understand the radial velocity technique of searching extrasolar planets and black holes; light deflection is derived approximately and used to understand gravitational microlensing and search for dark matter). There are 9 homeworks, a midterm exam and a final exam.

Astro 233: Topics in Astronomy (Sophomore Writing Seminar). This course introduces potential astronomy majors to the research in astronomy. The students learn, discuss and then write on selected topics in the forefront of astronomy. The students' essays are graded with substantial comments to help them improve their writing skills; then the students rewrite the essays. Some of the topics I covered include "Stellar exotica" (black holes and Gamma ray bursters), "Solar neutrinos", "Dark matter" and "Dark energy". Typically, I gave lectures to introduce the basic background materials, and then there were discussion sessions on several research papers; finally the students were ask to write an essay on these topics.

Astro 431: Introduction to Astrophysics I. Astro 431 and 432 focus on applying physical principles to understand astrophysical phenomena, while giving the students a broad overview of different branches of astronomy. Contemporary research topics were introduced whenever possible. One of the gratifying experiences in teaching the Astro 431-432 sequence has been to witness the students to develop greater interest in astrophysics, and to decide to pursue graduate study in astronomy (essentially all the students in my A431-A432 classes have entered graduate schools in physics or astronomy). Astro 431 covered all aspects of stars. These include standard material such as stellar structure, nuclear reactions, opacities, radiative transfer, convection, stellar atmospheres. Compact objects and various related high energy phenomena (X-ray sources and radio pulsars) were also introduced. Somewhat nonstandard material includes structure of brown dwarf and planet, solar neutrino problem (with MSW solution), stellar seismology, general relativity (which is used to study mass accretion disk around black hole) and sources of gravitational waves. There were 6 homeworks, a midterm exam and a final exam.

Astro 432: Introduction to Astrophysics II. Astro 432 covered important aspects of interstellar medium, galactic dynamics and cosmology. The ISM part includes basics of spectral line diagnostics, thermal instabilities and phases, plasma effects, hydrodynamics, shock waves and supernova remnants, MHD, star formation (Cloud equilibrium, Jeans instability, fragmentation, angular momentum transport, ambipolar diffusion). The stellar dynamics part includes basics of galactic structure, orbit theory (e.g., Lindblad resonances), relaxation, Boltzmann equations and Jeans equations, dark matter issues (flat rotation curves, Oort's problem, physics of microlensing and MACHO experiment), spiral density waves. The Cosmology part includes Fridemann universe, thermal history (inflation, neutrino and photon decouplings, nucleosynthesis, CMBR), classical cosmological tests (Hubble diagram), Jeans instability in expanding Universe, basics of galaxy formation. There were 6 homeworks, a midterm exam and a final exam.

Astro 511/Phys 525: Physics of Compact Objects. Astro 511 is a core graduate level course on high energy astrophysics, with focus on compact stars and related subjects. Research problems were discussed along the way. An important component of the course was to survey (generally in a quick and "low-brow" manner) the theoretical physics tools needed for understanding various astrophysical observations. New material includes aspects of active galactic nuclei and supermassive balck holes. There were 5 homeworks, a student research project, and a take-home final exam.

Astro 530 (Astrophysical Processes). The course is a comprehensive and rigorous treatment of many aspects of radiative processes relevant to astronomy. There were 6 long homeworks (including one final take-home exam) and a student research project (the student wrote a report and gave a presentation in class).

Astro 560/Phys 667 (Theory of Stellar Structure and Evolution). Astro 560 is a core graduate level course. In addition to the standard topics, I also covered stellar oscillations, binary stars, supernovae, stellar magnetic fields, and star formation. There were 5 homeworks (including a computer project), a student research project, and a final exam.

Astro 699a (Astrophysical Fluid Dynamics). This is a new course intended to introduce graduate students the basic physics and astrophysical applications of fluid mechanics and MHDs. In Fall 2006, this was taught as a seminar course. I plan to make it a full course in Fall 2008.

Astro 699b (High Energy Astrophysics Seminar). This seminar course (in Fall 2003) covered several topics of current research on high energy astrophysics, including supernova mechanisms, gamma-ray bursts, cosmic magnetic fields, etc. Various physics related to astrophysical fluid and plasma were introduced along the way.

II. Supervision of Students

Graduate Students

- **Wynn Ho** (Ph.D. 2003): He worked on neutron star oscillations, gravitational waves and radiative transfer in strong magnetic fields. He was awarded a Hubble fellow, and took it to KIPAC and MIT. He is now a research associate at Harvard CfA. Email: wynnho@slac.stanford.edu
- **Matt Van Adelsberg** (Ph.D. 2006): He worked on neutron star atmosphere modeling (spectrum and polarization). He is now a postdoc at U. Colorado/JILA. Email: mvanadel@jilau1.colorado.edu
- **Akiko Shirakawa** (Ph.D. 2007): She worked on warped accretion disks and nucleosynthesis in young neutron stars. She defended her thesis in May 2007 after several years on leave of absence (sick leave). She now works in the industry. Email: as189@cornell.edu
- **Chen Wang** (Ph.D. 2007): He was a student at NAOC (Beijing) but I was his main adviser (jointly with Dr. JinLin Han, who is an observer). He visited Cornell for several long periods in the last few years. He worked on observational constraints on pulsar kicks and wave modes/propagation in the magnetospheres of pulsars and magnetars. Email: wangchen@bao.ac.cn
- **Zach Medin** (Ph.D. expected 2008): He works on condensed matter in strong magnetic fields and pulsar/magnetar magnetosphere physics
- **David Tsang** (Ph.D. expected 2008): He works on wave modes in disks and photon propagation near Kerr black holes.
- **Wen Fu** (Ph.D. expected 2011): He works MHD effects in disks.

- In addition to the above, I have worked on research projects with two former Cornell graduate students: **Phil Arras** (now assistant professor at Univ. Virginia) (on neutrino transport in magnetic fields) and **Harld Pfeiffer** (now a postdoc at Caltech) (on nonlinear evolution of warped disks).
- I have served on the committee of about 8 Astronomy graduate students since 1998.

Undergraduate Student Research:

Although it is generally difficult for undergraduate students to carry out meaningful research in theoretical astrophysics, there are some exceptional Cornell students who are capable of doing that (usually, these are the students who are already taking graduate-level courses while in their junior or senior years). I have made a conscious effort to involve bright undergraduate students in research. This has required carefully proposing projects that can be tackled by undergraduates.

I was the senior thesis adviser of Paul Wiggins (A&EP,'99; Ph.D. in biophysics at Caltech; now a research Fellow at Whitehead Institute) and Carolyn Sealfon (A&S'00; Ph.D. in physics at U. Penn, now an Assistant Professor at West Chester Univ). Paul worked with me in 1998-1999; he published a refereed paper with me on tidal interaction around Kerr black holes. This work won him the 1999 Astronomical Society of New York undergraduate research prize, as well as the 2000 Dorothy & Fred Chau Award for undergraduate research from the School of Applied & Engineering Physics (I also received the award for supervising this project). Carolyn worked with me in 1999-2000 and wrote a senior honor thesis on equation of state in superstrong magnetic fields. I have also supervised the research projects of Brian Cameron ('03, now graduate student at Caltech), Marcus Woo ('3, now graduate student at Maryland), David Schwab ('03), Jared Gabor (Caltech '04, now graduate student at U. Arizona), Brad Austin (Columbia '06), and Tony Li ('08).

Freshman-Sophomore Advising

I have served as the adviser for 4-7 freshman/sophomore students every year since 1997. My goal in advising is to constitute a resource for the students and to aid them in dealing with both academic and personal issues. I try to build a relationship with the students by writing to them (via emails) regularly. I encourage the students to contact me and drop by my office whenever they like. I familiarize them with the various requirements of the College of Arts and Sciences, and also with further sources of information on academic issues in the University. I help each student in formulating short term and long term educational goals.