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Astrophysical, Planetary, and Space Sciences Program

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This report covers the astronomy-related activities of the Astrophysical, Planetary, and Space Sciences (APSS) Program, a component of the School of Computational Sciences (SCS) at George Mason University, for the period October 1, 2002 to September 30, 2003. The APSS program is also affiliated with the Center for Earth Observing and Space Research, and with the Department of Physics & Astronomy. Faculty and postdocs in the APSS program were J. Beall, P. Becker, K. Borne, S. D'Silva, M. Gliozzi, J. Guillory, M. Kafatos, D. Kniffen, A. Poland, R. Sambruna, S. Satyapal, M. Summers, L. Titarchuk, A. Vourlidas, J. Wallin, J. Weingartner, G. Withbroe, K. Wood, and J. Zhang. S. Roy was a visiting faculty member. Further program information is available at **www.scs.gmu.edu**.

1. INTRODUCTION

The interdisciplinary doctoral program in Computational Sciences and Informatics (CSI) offered by the School of Computational Sciences recognizes the importance of numerical computation as a unifying theme in modern research and education. The doctoral program, begun in the Fall of 1992, focuses on a number of specialty areas, including bioinformatics, computational chemistry, Earth systems and global change, computational mathematics, computational physics, space sciences, and computational statistics. The program emphasizes three intellectual elements: a common computational core; computationally intensive science courses; and doctoral research. APSS faculty advise astronomy students in the CSI doctoral program, and are involved in many ongoing collaborations with scientists at the Naval Research Laboratory and NASA/Goddard Space Flight Center. APSS maintains active relationships with a number of high-technology corporations in the Washington, D.C. area, and many associated faculty members participate in the Washington Area Astronomers Association, a regional organization of professional astronomers stretching from Charlottesville to Baltimore. In 2003, SCS/APSS began a new Space Weather program, combining solar physics and geophysics into a comprehensive research and academic unit, and the Department of Physics and Astronomy initiated a new Bachelor of Science Degree in Astronomy.

2. BLACK HOLE & NEUTRON STAR ACCRETION

P. Becker and graduate student T. Le have continued to study the physical processes operative in advection-dominated accretion disks surrounding non-rotating black holes. One focus was on the determination of the precise inner boundary conditions for advection-dominated accretion disks (Becker & Le 2003). In this work, the structure of the inner region of an advection-dominated accretion disk around a nonrotating black hole was explored by applying asymptotic analysis in the region just outside the event horizon. The viscous transport was described by the standard Shakura-Sunyaev prescription throughout the disk, including the inner region close to the horizon. One of the goals of this work was to explore the self-consistency of the Shakura-Sunyaev prescription by analyzing the causality of the viscous transport near the black hole. The effects of general relativity were incorporated in an approximate manner by utilizing a pseudo-Newtonian gravitational potential. Analysis of the conservation equations yielded unique asymptotic forms for the behaviors of the radial inflow velocity, the density, the sound speed, and the angular velocity. The specific behaviors are determined by three quantities; namely, the accreted specific energy, the accreted specific angular momentum, and the accreted specific entropy. The additional requirement of passage through a sonic point further constrains the problem, leaving only two free parameters. The detailed results confirm that the Shakura-Sunyaev viscosity yields a well-behaved flow structure in the inner region that satisfies the causality constraint. It was also demonstrated that the velocity distribution predicted by the pseudo-Newtonian model agrees with general relativity in the vicinity of the horizon. The asymptotic expressions obtained therefore yield useful physical insight into the structure of advection-dominated disks, and they also provide convenient boundary conditions for the development of global models via numerical integration of the conservation equations. Although the focus of this work was on advection-dominated flows, the results obtained are also applicable to disks that lose matter and energy, provided the loss rates become negligible close to the event horizon. This work appeared in the ApJ in May 2003.

In more recent work, Becker and Le have examined the consequences of the presence of standing shocks in hot accretion disks for the formation of the relativistic outflows (jets) of matter commonly observed in systems containing black holes. The strongest outflows occur in the radio-loud systems, which may contain hot, advection-dominated accretion disks. In these systems, the binding energy of the accreting gas is emitted primarily in the form of particles rather than radiation. However, no comprehensive model for the disk structure and the associated outflow has yet been produced. In this work, Becker and Le have constructed the first self-consistent model for an inviscid, advection-dominated black hole accretion disk, including a standing shock in which particles are efficiently accelerated up to relativistic energies before escaping from the disk. The shock is supported by the centrifugal barrier in the disk. The theoretical analysis parallels the study of cosmic-ray acceleration in supernova shock waves. The results include the structure of the disk and the energy and spatial distribution of the relativistic particles, which may escape to form the observed outflows. Applications to viscous disks are currently being explored.

Accretion onto compact objects in X-ray binaries (black hole, neutron star [NS], white dwarf) is characterized by nonuniform flow density profiles. Such an effect of heterogeneity in the presence of gravitational forces and pressure gradients causes Rayleigh-Taylor gravity waves. They should be seen as quasi-periodic wave oscillations (QPOs) of the accretion flow in the transition (boundary) layer between the Keplerian disk and the central object. L. Titarchuk has shown that the main QPO frequency, which is very close to the Keplerian frequency, is split into separate frequencies (hybrid and lower branch) under the influence of the gravitational forces in the rotational frame of reference. The observed low and high QPO frequencies are an intrinsic signature of Rossby gravity waves (large-scale fluid motion in the rotational frame of reference). He elaborated the conditions for the density profile for which the gravity-wave oscillations are stable. A comparison of the inferred QPO frequencies with QPO observations was presented. Titarchuk finds that the hectohertz frequencies detected from NS binaries can be identified as the lower-branch frequencies of the gravity-wave oscillations. He also predicted that an observer will see the double NS spin frequency during the NS long (super) burst events, when the pressure gradients and buoyant forces are suppressed. The Coriolis force is the only force that acts in the rotational frame of reference, and its presence causes perfect coherent pulsations with a frequency twice that of the NS spin. The QPO observations of NS binaries have established that the high QPO frequencies do not go beyond a certain upper limit. Titarchuk explained this observational effect as a result of the density profile inversions. In particular, he demonstrated that a particular problem of the gravity waves in the rotational frame of reference in the approximation of very small pressure gradients is reduced to the problem of the classical oscillator in the rotational frame of reference that was previously introduced and applied for the interpretation of the kHz QPO observations in some previous publications. The Rossby type of Rayleigh-Taylor gravity waves must be present, and the related QPOs should be detected in any system where the gravity, buoyancy, and Coriolis force effects cannot be excluded (even in the Earth and solar environments).

L. Titarchuk has described a method for the determination of black-hole masses based on information inferred from high-energy spectra. It is required that the spectral energy distribution consist of thermal and Comptonized components. One can then, in principle, infer the depth of the gravitational potential well for sources of known distance. The thermal component is inferred by the integration of a blackbody spectral form over the disk. He assumes that the color temperature distribution in the disk has a specific shape given by the Shakura-Sunyaev (1973) disk model which goes to zero at the inner disk radius and at infinity and has a maximum at 4.2 Schwarzschild radii. In this formulation there is only one parameter, the so called color correction factor, relating the apparent temperature to the effective temperature which characterizes the thermal emission component. He has made use of improved Galactic black hole binary dynamical mass determinations to derive, in effect, an empirical calibration of this factor. He uses this to present observational data for representative objects of several classes; Galactic black hole X-ray binaries, narrow line Seyfert galaxies (NLS1), and ‘‘ultra-luminous’’ extragalactic X-ray sources (ULX). Titarchuk argues that this approach can potentially fill a void in the current knowledge of NLS1 and ULX properties, and he discusses how a deeper understanding of both classes can yield new insights into the formation and mass distribution of cosmic black holes.

3. HIGH-ENERGY RADIATIVE TRANSFER

P. Becker (2003) has obtained an exact, closed-form expression for the time-dependent Green’s function solution to the Kompaneets equation. The result, which is expressed as the integral of a product of two Whittaker functions, describes the evolution in energy space of a photon distribution that is initially monoenergetic. Effects of spatial transport within a homogeneous scattering cloud are also included within the formalism. The Kompaneets equation that is solved includes both the recoil and energy diffusion terms, and therefore the solution for the Green’s function approaches the Wien spectrum at large times. This was not the case with earlier analytical solutions that neglected the recoil term and were therefore applicable only in the soft-photon limit. It is shown that the Green’s function can be used to generate all of the previously known steady-state and time-dependent solutions to the Kompaneets equation. The new solution allows the direct determination of the spectrum, without the need to numerically solve the partial differential equation. It is therefore much more convenient for data analysis purposes. Based upon the Green’s function, Becker derived a new, exact solution for the variation of the inverse-Compton temperature of an initially monoenergetic photon distribution. Furthermore, a new time-dependent solution for the photon distribution resulting from the reprocessing of an optically thin bremsstrahlung initial spectrum with a low-energy cutoff was also obtained. Unlike the previously known solution for bremsstrahlung injection, the new solution possesses a finite photon number density, and therefore it displays proper equilibration to a Wien spectrum at large times. These results have particular significance for the interpretation of emission from variable X-ray sources, such as the production of hard X-ray time lags and the Compton broadening of iron lines. This research was reported in a paper published in MNRAS in July 2003. As an outgrowth of this work, a new formula was derived for the exact evaluation of a family of integrals containing the product of two Whittaker *W*-functions. A paper describing this work was accepted for publication in the Journal of Mathematical Physics.

L. Titarchuk investigated the effects of bulk motion Comptonization on the spectral formation in a converging flow onto a black hole. The problem is tackled by means of both a fully relativistic, angle-dependent transfer code and a semianalytical, diffusion approximation method. He found that a power-law high-energy tail is a ubiquitous feature in converging flows and that the two approaches produce consistent results at large enough accretion rates when photon diffusion holds. The semianalytical approach is based on an expansion in eigenfunctions of the diffusion equation. Contrary to previous investigations based on the same method, Titarchuk finds that although the power-law tail at extremely large energies is always dominated by the flatter spectral mode, the slope of the hard X-ray portion of the spectrum is dictated by the second mode and it approaches $\Gamma = 3$ at large accretion rates, irrespective of the model parameters. The photon index in the tail is found to be largely independent of the spatial distribution of soft seed photons when the accretion rate is either quite low (less than or similar to 5 in Eddington units) or sufficiently high (greater than or similar to 10). On the other hand, the spatial distribution of photon sources controls the photon index at intermediate accretion rates, when Γ switches from the first to the second mode. The analysis confirms that a hard tail with photon index $\Gamma < 3$ is produced by the upscattering of primary photons onto infalling electrons if the central object is a black hole.

Using a large quantity of Rossi X-Ray Timing Explorer data presented in the literature, L. Titarchuk offered a detailed investigation into the accuracy of the quasi-periodic oscillation (QPO) frequency determination. The QPO phenomenon seen in X-ray binaries is possibly a result of the resonance of the intrinsic (eigen) oscillations and harmonic driving forces of the system. He shows that the resonances, in the presence of the damping of oscillations, occur at frequencies that are systematically and randomly shifted with respect to the eigenfrequencies of the system. The shift value strongly depends on the damping rate that is measured by the half-width of the QPO feature. Taking into account this effect, he analyzed the QPO data for four Z sources, Scorpius X-1, GX 340+0, GX 5-1, and GX 17+2, and two atoll sources, 4U 1728-34 and 4U 0614+09. The Transition-Layer Model (TLM) predicts the existence of the invariant quantity δ, an inclination angle of the magnetospheric axis with respect to the normal to the disk. Titarchuk calculated δ and the error bars of δ using the resonance shift, and found that the inferred δ-values are consistent with constants for these four Z sources, in which horizontal-branch oscillation and kilohertz frequencies have been detected and correctly identified. It is shown that the inferred values of δ are in the range between 5.5 and 6.5 degees. Titarchuk concludes that the TLM seems to be compatible with the data.

L. Titarchuk has interpreted the correlation over 6 orders of magnitude between the high frequency $\nu_{\rm high}$ and the low frequency $\nu_{\rm low}$ in quasi-periodic oscillations (QPOs) found by Psaltis, Belloni, & van der Klis for black hole (BH) and neutron star (NS) systems and then extended by Mauche to white dwarf (WD) binaries. The observed correlation strongly constrains theoretical models and provides clues to understanding the nature of the QPO phenomena at large. He argues that the observed correlation is a natural consequence of the Keplerian disk flow adjustment to the innermost sub-Keplerian boundary conditions near the central object that ultimately leads to the formation of the sub-Keplerian transition layer (TL) between the adjustment radius and the innermost boundary (the star surface for the NS and WD and the horizon for the BH). In the framework of the TL model, $\nu_{\rm high}$ is related to the Keplerian frequency at the outer (adjustment) radius ν_K, and $\nu_{\rm low}$ is related to the magnetoacoustic oscillation frequency ν_{MA}. Using a relation between ν_{MA}, the magnetic and gas pressure, and the density and the hydrostatic equilibrium condition in the disk, Titarchuk infers a linear correlation between ν_K and ν_{MA}. Identification of $\nu_{\rm high}$, $\nu_{\rm low}$ with nu_K, ν_{MA}, respectively, leads him to the determination of $H/r_{\rm out} = 1.5\times10^{-2}$ and $\beta = 0.1$ (where H is the half-width of the disk, β is the ratio of magnetic pressure to gas pressure, and $r_{\rm out}$ is the outer radius). He estimates the magnetic field strength near the TL outer radius for BHs, NSs, and WDs. The fact that the observed high-low frequency correlation over 6 orders of magnitude is valid for BHs, NSs, and down to WDs strongly rules out relativistic models for QPO phenomena. He comes to the conclusion that the QPO observations indicate the adjustment of the geometrically thin disk to sub-Keplerian motion near the central object. This effect is a common feature for a wide class of systems, starting from WD binaries up to BH binaries.

L. Titarchuk has explained why it is possible to detect directly X-ray emission from near the surface of the neutron star (NS) in SAX J1808.4-3658 but not in most other low-mass X-ray binaries (LMXBs), with the exception that emission from the surface can be seen during burst events. He shows that the X-ray emission from SAX J1808.4-3658 mostly originates in the Comptonization process in a relatively optically thin hot region (with an optical depth τ_0 around 4 and temperature around 20 keV). Such a transparent region does not prevent us from detecting coherent X-ray pulsations due to hot spots on the NS surface. Titarchuk gives a precise model for the loss of modulation: such suppression of the quasi-periodic oscillation (QPO) amplitude due to scattering can explain the disappearance of kilohertz QPOs with increasing QPO frequency. He also formulates general conditions under which the millisecond X-ray pulsation can be detected in LMXBs, and he demonstrates that the observed soft phase lag of the pulsed emission is a result of the downscattering of the hard X-ray photons in the relatively cold material near the NS surface. In the framework of this downscattering model, he proposes a method to determine the atmospheric density in that region from soft-lag measurements.

L. Titarchuk, D. Kazanas (NASA/GSFC), and P. Becker formulated and solved the diffusion problem of line photon propagation in a bulk outflow from a compact object (black hole or neutron star) using a generic assumption regarding the distribution of sources of line photons within the outflow. Thomson scattering of the line photons within the expanding flow leads to a decrease of their energy which is of first order in v/c, where v is the outflow velocity and c is the speed of light. They demonstrate that the emergent line profile is closely related to the escape time distribution of photons diffusing through the flow (the light curve), and consists of a broad redshifted feature. They analyzed the line profiles for the case of a general outflow density distribution. The redshifted lines are intrinsic properties of the powerful outflow that are supposed to exist in many compact objects. This work is scheduled for publication in the ApJ in November 2003.

L. Titarchuk, N. Shaposhnikov, and F. Haberl (MPIEP), analyzed a set of Type I X-ray bursts from the low mass X-ray binary 4U 1728-34, observed with Rossi X-ray Timing Explorer (RXTE). An analytical model for X-ray spectral formation in the neutron star (NS) atmosphere during a burst was implemented. The dependence of the neutron star mass and radius with respect to the assumed distance to the system was inferred using the analytical model for the X-ray burst spectral formation. The model behavior clearly indicates that the burster atmosphere is helium-dominated. The results strongly favor the soft equation of state (EOS) of NS for 4U 1728-34. In particular, they find that the distance to the source should be within the range 4.5-5.0 kpc. They obtain a rather narrow constraint for the NS radius in the range 8.7-9.7 km, and for the mass a result in the interval 1.2-1.6 solar masses. They also explain the temporal behavior of the red-shift corrected burst flux during the radial expansion episodes, and put forth a dynamical evolution scenario for the NS–accretion disk geometry during which an expanded envelope affects the accretion disk and increases the area of the neutron star exposed to the Earth observer. This scenario successfully explains the timing characteristics and peak flux variations observed during the burst expansion stage, which is now believed to be a common phenomenon. The new interpretation provides a useful method for the estimation of the inclination angle, which leads to the value of 50 degrees for 4U 1728-34.

4. SOLAR PHYSICS

S. D'Silva contributed toward the theoretical development of Time-Distance Helioseismology and also helped to progress its adaptation to Helioseismic Tomography. Time-distance helioseismology is a method to study the interior of the Sun by computing travel times of individual acoustic wavepackets as they propagate through the Sun between two spatially separated locations on its surface. Helioseismic tomography is a form of the tomographic techniques adapted to image the interior of the Sun from observations of the acoustic oscillations at the surface. Currently he is involved in magnetohydrodynamic tomography that would image the magnetic fields under the surface of the Sun using observations of the surface acoustic oscillations.

S. D'Silva studied the morphology and dynamics of sunspots. This work involved the dynamics of the progenitors of sunspots—magnetic flux tubes — from the region of their origin (200,000 km beneath the solar surface) through a highly turbulent, convectively unstable region. The flux tube was modeled to be a one-dimensional string with all properties of a magnetic flux tube allowed to move in the three-dimensional space of the convection zone. A number of dynamical and morphological properties of sunspots could be successfully explained if the magnetic field strength of the flux tubes at the region of their origin were of the order of 100,000 G. Currently he is conducting magnetohydrodynamical calculations of magnetic flux transport to understand the morphology and dynamics of all magnetically active regions on the surface of the Sun, from tiny Ephemeral Regions to sunspots and plages.

S. D'Silva analyzed and identified solar coronal mass ejection (CME) sources for 27 major geomagnetic storms occurring between 1996 and 2000. Observations of CMEs and their solar surface origins were obtained from the Large Angle and Spectrometric Coronagraph (LASCO) and the EUV Imaging Telescope (EIT) instruments on the SOHO spacecraft. The identification has two steps. The first step is to select the candidate front-side halo (FSH) CMEs using a fixed, 120 hr time window. The second step is to use solar wind data to provide further constraints, e.g., an adaptive time window based on the solar wind speed of the corresponding interplanetary CMEs. He finds that 16 of the 27 (59%) major geomagnetic storms are identified with unique FSH CMEs. Six of the 27 events (22%) are associated with multiple FSH CMEs. These six events show complex solar wind flows and complex geomagnetic activity, which are probably the result of multiple halo CMEs interacting in interplanetary space. A complex event occurs when multiple FSH CMEs are produced within a short period. Four of the 27 (15%) events are associated with partial-halo gradual CMEs emerging from the east limb. The surface origin of these events is not known because of a lack of any EIT signature. D'Silva believes that they are longitudinally extended CMEs having a component moving along the Sun-Earth connection line. One of the 27 major geomagnetic storms is caused by a corotating interaction region. He finds an asymmetry in the longitudinal distribution of solar source region for the CMEs responsible for major geomagnetic storms. They are more likely to originate from the western hemisphere than from the eastern hemisphere. In terms of latitude, most geoeffective CMEs originate within a latitude strip of $\pm$ 30 degrees. The average transit time for a solar CME to arrive at near-Earth space is found to be 64 hr, while it takes 78 hr on average to reach the peak of the geomagnetic storm. There is a correlation between CME transit time T from the Sun to the near-Earth space and the CME initial velocity V at the Sun, which can be simply expressed as $T = 96\text{-}(V/21)$, where T is measured in hours and V is measured in kilometers per second. D'Silva also finds that while these geoeffective CMEs are either full-halo CMEs (67%) or partial-halo CMEs (30%), there is no preference for them to be fast CMEs or to be associated with major flares and erupting filaments.

S. D'Silva computed the magnetic helicity injected by transient photospheric horizontal flows in six solar active regions associated with halo coronal mass ejections (CMEs) that produced major geomagnetic storms and magnetic clouds (MCs) at 1 AU. The velocities are computed using the local correlation tracking (LCT) method. The computations cover time intervals of 110 150 hr, and in four active regions the accumulated helicities due to transient flows are factors of 8–12 times larger than the accumulated helicities due to differential rotation. As was first pointed out by D‘‘moulin and Berger, the helicity computed with the LCT method yields not only the helicity injected from shearing motions but also the helicity coming from flux emergence. D'Silva compared the computed helicities injected into the corona with the helicities carried away by the CMEs using the MC helicity computations as proxies to the CME helicities. If we assume that the length of the MC flux tubes is l – 2 AU, then the total helicities injected into the corona are a factor of 2.9 – 4 lower than the total CME helicities. This study, at least partially, clears up some of the discrepancies in the helicity budget of active regions because the discrepancies appearing in the present work are much smaller than the ones reported in previous studies.

G. Withbroe developed a database containing general information, types of measurements, orbital data, launch date, and mission status for all current and planned space missions with solar-terrestrial instrumentation. The database will be made available via the NASA International Living With a Star website. Withbroe is serving on the NASA Sun-Climate Task Force, which is defining for the NASA Living With a Star program an appropriate focus for research into the effects of solar variability on terrestrial climate and is also seeking to encourage interdisciplinary collaborations on this topic.

5. EXTRAGALACTIC ASTRONOMY & COSMOLOGY

S. Satyapal, in collaboration with M. Luhman (IDA), J. Fischer (NRL), and others, continued her studies on infrared spectroscopy of ultraluminous infrared galaxies (ULIRGs). These results have shown that, contrary to expectation, the most luminous galaxies display the weakest emission lines from ionized and photodissociated gas. They show that this result is consistent with an increase in dust absorption of ionizing photons in the most luminous galaxies, a result that will have serious consequences on the usefulness of similar emission line observations of high redshift protogalaxies, thought to resemble the local ULIRGs observed in the study (Luhman *et al.* 2003).

Together with R. Sambruna and graduate student R. Dudik, Satyapal continued her work on a joint infrared and X-ray investigation of LINER galaxies. This is the first comprehensive study of the mid-infrared fine structure line emission of LINERs. These results have been compared with similar observations of starburst galaxies and AGNs. They find that LINERs very clearly fall between starbursts and AGNs in their mid-IR fine structure line spectra. Chandra imaging observations of the LINERs reveal hard nuclear point sources morphologically consistent with AGNs in 2/3 of the sample. In addition, X-ray morphologies show a clear trend with infrared brightness. They find that most LINERs that show a single dominant hard compact X-ray core are IR-faint while most LINERs that show scattered X-ray sources consistent with a starburst are IR-bright. A comparative X-ray/mid-IR spectroscopic investigation of LINERs reveals some puzzling results. They find several sources that display a strong hard X-ray nucleus but show no high excitation emission lines in the infrared. Conversely, it is found that objects that show a prominent high excitation spectrum in the IR display weak X-ray emission. With the advent of SIRTF, and future IR missions such as Herschel and NGST, it is increasingly critical to determine the origin of these multiwavelength anomalies (Satyapal, Sambruna, & Dudik 2003).

R. Sambruna continued her study on extragalactic jets using multiwavelength imaging data collected with Chandra, HST, and ground-based radio telescopes. Together with graduate student J. Gambill, L. Maraschi and F. Tavecchio (Oss Brera, Milan), and C. Urry (Yale University), Sambruna studied a sample of 17 radio jets observed at X-ray and optical wavelengths. The team found a high detection rate at high energies on kiloparsec scales, with 60% of all jets detected at both wavelengths. The origin of the X-ray emission from most jets is inverse Compton scattering off the Cosmic Microwave Background photons (IC/CMB).

Sambruna and Postdoctoral Fellow M. Gliozzi are studying the nuclear X-ray emission of low-power radio galaxies. Using proprietary and archival data collected with XMM-Newton and Chandra, they examined the spectral and timing properties of NGC 4261 and NGC 6251. They found the presence of relatively strong (EW$\sim$200 eV) Fe emission lines at 6–7 keV, probably originating in an accretion disk around the central black hole. Flux and spectral variability are also present in both cases, with a trend (softer spectrum in high intensity state) similar to radio-quiet Seyferts. The results were published in Sambruna *et al.* (2003) and Gliozzi *et al.* (2003).

In collaboration with K. Lewis and M. Eracleous (PSU), Sambruna published optical line measurements of a sample of Weak-Line Radio Galaxies, low-power radio galaxies characterized by a low [OII]/[OIII] flux ratio. They found that most of these sources host bone fide LINERs in their nuclei (Lewis *et al.* 2003).

J. Gambill and R. Sambruna have focused on the analysis and interpretation of X-ray, optical and radio data collected for a sample of radio quasars and radio galaxies. These objects are all classified as radio-loud active galactic nuclei and exhibit extended radio structures of varying length, orientation and morphological class. This sample was observed with the Chandra X-ray Observatory and the Hubble Space Telescope with the intention of discovering the X-ray and optical counterparts of the known radio jets (as observed with the Very Large Array [VLA]). With Chandra, the X-ray emission from the nucleus can be isolated from the extended (kiloparsec-scale) jet emission and other extended components (e.g. diffuse circumnuclear gas), so that X-ray observations can be compared in multiwavelength studies. The unprecedented resolution of Chandra has led to discoveries of X-ray jets and has enabled significant progress in the study of X-ray emission from the cores of radio-loud quasars. With multiwavelength data at high resolution, Gambill and Sambruna are systematically studying the multiple components of the AGNs: the analysis of the cores is presented in Gambill *et al.* (2003) and the results for the X-ray detected AGN jets are in preparation (Sambruna, Gambill *et al.*). They have also obtained follow-up X-ray and optical observations for two of the sources in the sample. These observations will allow detailed study of the newly detected high-energy jet knots in these sources, constraining spectra for individual knots in the optical and X-ray bands.

D. Donato, M. Gliozzi, and R. Sambruna presented Chandra observations of the X-ray environment of a sample of 6 BL Lacertae objects. The improved sensitivity of the ACIS experiment allows them to separate the core X-ray emission from the contribution of diffuse emission from the host galaxy/cluster scales. Within the short (2-6 ks) ACIS exposures, they find evidence for diffuse X-ray emission in 3 sources (BL Lac, PKS 0548-322, and PKS 2005-489). The diffuse emission can be modeled with a King profile with

$\beta \sim 0.3-0.6$, core radii $r_c \sim 15-28$ kpc, and 0.4-5 keV luminosities in the range 1041-1042 erg s^{-1}. In the remaining 3 sources, one (3C 371) has a radial profile entirely consistent with an unresolved source, while two (1ES 2344+514 and 1ES 2321+419) show evidence for weak diffuse emission on kpc scales. These results support current models for radio-loud AGN unifying BL Lacs and FRI radio galaxies through the orientation of their jets. In PKS 0548-322 and PKS 2005-489, they also find evidence for diffuse emission on cluster scales, although the spatial properties of this emission are not constrained. The temperature ($kT \sim 3-5$ keV) and luminosity in the 0.4-5 keV range ($L \sim 10^{42}$ erg s^{-1}) of the cluster gas are typical of normal clusters. Interestingly, these are the two brightest sources of the sample, suggesting a link between environment and nuclear activity.

D. Donato focused on the analysis and interpretation of X-ray data from Active Galactic Nuclei (AGNs) and in particular from the subclass of radio-loud AGNs. Orientation-based unification models for Active Galactic Nuclei have been successful in explaining the rich variety of observed properties in the various classes of AGNs. According to these schemes, the various AGNs are the same intrinsic object (powered by accretion of the host galaxy gas onto a supermassive black hole through a dense torus and an accretion disk), seen at different orientation angles with respect to a preferred axis. In the case of radio-loud AGNs, the different subclasses are due to the different orientations of the relativistic jet coming from the supermassive black hole, with blazars (BL Lacertae objects and Flat Spectrum Radio Quasars) corresponding to the more aligned sources, and radio galaxies (Fanaroff-Riley I and II) being their parent populations. Previous studies at radio, IR, and optical wavelengths show that for BL Lacs (the relatively local, low-luminosity version of blazars) the parent population is most likely represented by FR I radio galaxies. Donato analyzed Chandra observations of the X–ray environment of a sample of BL Lacertae objects, separating the core X-ray emission from the contribution of diffuse emission from the host galaxy/cluster scales. Currently, he is working on Chandra and XMM-Newton data of a sample of FR I radio galaxies. The main purpose of this work is to confirm the new ideas (not in agreement with the unification model for AGN) that most of the FR I's harbor an unresolved central nuclear source and that the optical core emission is strongly correlated with the radio core emission. These ideas suggest a lack of the obscuring torus and of the thermal disk emission around the supermassive black hole.

M. Gliozzi and R. Sambruna focused on the analysis and interpretation of X-ray data from AGNs. One of the fundamental open questions in our understanding of AGNs is the difference between radio-loud (RL) and radio-quiet (RQ) objects. While the ultimate source of power is thought to be the same in both AGN classes (i.e., accretion of gas onto a supermassive black hole), there are subtle but systematic differences in the continuum and line properties from radio to optical/UV wavelengths. Optical observations indicate that the environs of both RL and RQ sources do not differ significantly, thus restricting the origin of their dichotomy to the innermost regions of the AGN, namely to the properties of the central black hole and/or the accretion process. X-ray spectra are one of the tools by which we can achieve progress in our understanding of the nature of accretion in AGNs and look for differences in the structure of the accretion flows of RL and RQ AGNs. This is because the X-rays originate in the innermost, hottest parts of the accretion flow, and thanks to their high penetrating power, they carry to us features both in absorption and in emission which are diagnostic of the conditions of the matter around the supermassive black hole. The X-ray flux from AGNs exhibits variability on time scales shorter than any other energy band, indicating that the emission occurs in the innermost regions of the central engine. Therefore, the study of the X-ray variability provides an additional powerful tool to probe the extreme physical processes operating in the inner parts of the accretion flow close to the event horizon of the black hole.

S. Roy, M. Roy, M. Kafatos, and H. Kandpal (New Delhi) have already developed a dynamical multiple scattering theory for the scattering of partially coherent electromagnetic waves from an anisotropic random medium. The shift and the broadening of the spectral lines have been shown to be dependent on the parameters of the medium. The induced correlation has also been shown to be responsible for the shift and broadening of the spectral lines. In quasars, jets are common. They imply a kind of anisotropic medium around the quasar. The contributions of this type of shift (which is Doppler-like) have been calculated for the high redshift quasars. This is a purely local effect as it is due to the scattering from the medium around quasars. The data from the Veron Cetti Catalog for 23,000 quasars have been analyzed for the Hubble diagram and the ‘‘bulge’’ for high redshifts in the diagram can be explained by taking a certain range of the medium parameters. These medium parameters are compatible with the plasma medium found in laboratory experiments. In the next phase of the work, the values of the parameters and the density of the medium which give rise to the observed redshift and broadening of the medium in actual laboratory experiments will be determined. A grant was recently obtained from the Department of Science and Technology, Government of India, to perform such experiments at the National Physical Laboratory, New Delhi. Kandpal and his group will perform the experiment. In another effort, a multiple scattering theory is being developed using a higher-order Born approximation as well as the Rytov approximation. This will be applicable to a medium with high densities.

K. Borne is working with colleagues at the NASA Goddard Space Flight Center on various scientific data mining research projects. One such project is devoted to searching several large multi-wavelength astronomical databases for distinguishing properties of the ULIRG (Ultra-Luminous IR Galaxy) population, which can then be used to find new ULIRG candidates in the large astronomical survey databases now becoming available worldwide. In another data mining project with D. Bazell (Eureka Scientific), K. Borne is developing new techniques for discovering new classes and classifying large numbers of objects in new previously unclassified astronomical databases.

K. Borne is working with colleagues at STScI and Madrid on a large HST imaging survey of ULIRGs and on a new ground-based imaging study of intermediate-luminosity IR galaxies. He is a collaborator on several ground-based telescope projects world-wide to study the class of multiple-merger ULIRGs that he and his colleagues discovered. He is also working with D. Patton (University of Trent) on an HST imaging survey of moderate-redshift binary galaxies from the CNOC2 survey.

K. Borne is collaborating with E. Shaya (University of Maryland), on the SIM (NASA's Space Interferometry Mission) science team, to develop models for the dynamical history and current kinematics of the Local Group of galaxies, to be tested when the first-ever measurements of the proper motions of nearby galaxies are obtained with SIM early in the next decade. K. Borne is a member of the NSF-funded project to develop a framework for the National Virtual Observatory (NVO). He is contributing to the NVO project in the areas of: scientific data mining, grid and web services, science use cases, and education and public outreach.

D. Kniffen has been on an Intergovernmental Personnel Act (IPA) assignment in the Astronomy and Physics Division (APD) in the Office of Space Science at NASA Headquarters. As a Program Scientist he has scientific oversight of three operating missions, NASA's Chandra X-ray Observatory, and the High Energy Transient Explorer (HETE), and for NASA's involvement in ESA's INTErnational Gamma Ray Laboratory (INTEGRAL). He also has responsibility for the scientific oversight in the development of the Gamma Ray Large Area Space Telescope (GLAST) mission to be launched in 2006. These missions all reside within the Structure and Evolution of the Universe Theme within the APD. In addition he shares responsibility for the high-energy astrophysics component of the annual Astronomy and Astrophysics Research and Analysis (APRA) funding opportunity.

6. COMPUTATIONAL ASTROPHYSICS AND DYNAMICAL ASTRONOMY

During the last year, J. Wallin and graduate student S. Antunes completed work developing a simulation code that incorporates softened-particle hydrodynamics (SPH) and tree-gravity. The code has been optimized for use on a Beowulf cluster, and is being used to investigate several questions in interacting galaxies. Specifically, it is being used to investigate how the large-scale dynamical disturbances due to the interactions couple with the observed star formation in collisional ring galaxies. By doing detailed comparisions between well-observed ring galaxies and numerical models of the collisions that formed them, they hope to be able to rule out specific mechanisms linking the star formation to the gas dynamics. Several papers related to the optimization of this code were presented at conferences.

J. Wallin worked with graduate student G. Page to numerically model the distribution of weakly interacting massive particles (WIMPs) trapped in orbits around the Sun. Previous studies examining the distribution of WIMPS in solar orbits have relied on the diffusion approximation. This approximation may fail due to the small number of scatterings that these particles undergo before trapped particles are again ejected by energetic elastic collisions with solar nuclei.

J. Wallin collaborated with graduate student J. Harrell on simulations of the cratering impacts on asteroids. Previous simulations, using axisymmetric 3D codes, have shown that the low tensile strength of these bodies is essential to the formation of large craters without breaking the asteroids apart. The new work being undertaken extends this work by modeling fully three-dimensional collisions of these encounters.

K. Borne joined the GMU faculty in summer 2003. He is continuing his collaboration with J. Wallin and A. Antunes to develop a numerical simulation code for interacting starbursting galaxies. The code includes both gravitational and hydrodynamic effects, plus astrophysical effects, such as star formation.

J. Guillory and graduate student R. Youmans have begun investigations and comparisons for dust grains and micrometeoroids produced by ablation from high-eccentricity comets. They have now simulated gravitational orbits for a distribution of comet fragments with a variety of initial velocities and masses and with emission rates a simple (inverse-square) function of the Sun-comet distance. This work is a preliminary study that will lead to a larger set of simulations of dust generation and dynamics, and to the determination of the zodiacal light distribution based on the physics of the dust scattering.

7. RELATIVISTIC ASTROPHYSICS

P. Becker and graduate student K. Wolfram have begun to investigate the propagation of neutrinos through the interiors of ''ultracompact'' stars, which are objects so small that their surfaces lie within the photon orbital radius. Neutrinos propagating through the interiors of such objects can experience a significant blueshift due to the form of the interior metric. While ordinary neutron stars are essentially transparent to neutrinos, ultracompact objects may be more opaque due to the dependence of the neutrino interaction cross section on the energy of the neutrino. Since this cross section increases rather strongly as a function of the neutrino energy, the mean free path may be quite small near the center of the star, and therefore the neutrinos may be able to reach equilibrium with the ordinary matter in that region. Becker and Wolfram are studying this phenomenon using relativistically correct Monte-Carlo simulations as well as approximate analytical models.

J. Beall and J. Guillory continue their collaboration with D. Rose (Mission Research Corporation, Albuquerque, NM), investigating the physics governing the propagation of jets of material originating in the centers of Active Galactic Nuclei (AGNs), moving outward, and interacting with ambient material in the broad-line and narrow-line regions (BLR and NLR) of AGNs. It is believed that the dominant energy loss mechanism for such jets is via plasma (collective) processes. In the regime of parameters likely to be important for astrophysical applications, the research models the plasma waves generated by the interaction of the AGN jet with the ambient medium. To do this, it is necessary to solve a time-dependent system of extremely stiff, coupled, differential equations. The code used for this problem solves for the time-dependent, spatially averaged intensity of plasma waves generated by the jet as it propagates through the ambient medium. The code thus allows estimates of the propagation length and strength of the interaction of the relativistic jet. Beall, Guillory, and Rose are currently extending the model by modifying the Landau damping rate to take into account the significant jet heating of the ambient medium, which produces a high-energy tail on the velocity distribution of the gas particles. This in turn changes the Landau damping rate, the time dependence of the wave energies, and, consequently, the energy loss rates for the jets. These results are being used to refine current estimates of jet propagation lengths and the heating rates of the ambient medium.

J. Beall and J. Guillory have begun a collaboration with S. Schindler of the Institute of Astrophysics, University of Innsbruck, Innsbruck, Austria, and S. Collagrancesco, INAF, Astronomical Observatory of Rome, Rome, Italy, focusing on the relationship between AGN jet heating and the dynamics of the intracluster gas in clusters of galaxies.

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