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This report covers the astronomy-related activities of the Center for Earth Observing and Space Research (CEOSR), a component of the School of Computational Sciences (SCS) at George Mason University, for the period October 1, 2001 to September 30, 2002. Faculty and postdocs in the CEOSR program were J. Beall, P. Becker, R. Ellsworth, J. Guillory, M. Kafatos, L. Ozernoy, R. Sambruna, S. Satyapal, M. Summers, L. Titarchuk, A. Vourlidas, J. Wallin, K. Wood, R. Yang, and J. Zhang. S. Roy was a visiting faculty member. Further program information is available at http://www.ceosr.gmu.edu.

1. INTRODUCTION

We begin by noting the sad passing of Dr. Leonid Ozernoy, a respected colleague and friend. Dr. Ozernoy died on 28 February 2002 after a long illness. He received his doctorate in physics and mathematics in 1971 from the P. N. Lebedev Physics Institute in Moscow, where he worked as a senior research scientist from 1971-1986. He completed his dissertation under the guidance of Dr. Vitaly Ginzburg, one of the most senior Soviet astrophysicists. Dr. Ozernoy was a prolific scientist with a broad array of interests in fields as diverse as cosmology, active galaxies and quasars, black holes, pulsars, and the evolution of the solar system. He made many fundamental contributions to these areas as author or coauthor of over 280 scientific publications, as well as several books. In particular, he performed groundbreaking studies of the central black hole in the Galactic nucleus, and the astrophysics of magnetoid objects, postulated to exist in the centers of active galaxies.

The interdisciplinary doctoral program in Computational Sciences and Informatics 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. SCS Space Sciences faculty are involved in many ongoing collaborations with scientists at the Naval Research Laboratory and NASA/Goddard Space Flight Center. SCS also maintains active relationships with a number of high-technology corporations in the Washington, D.C. area. Many members of CEOSR participate in the Washington Area Astronomers Association, a regional organization of professional astronomers stretching from Charlottesville to Baltimore.

2. OBSERVATIONAL ASTRONOMY & MULTIFREQUENCY DATA ANALYSIS

Jie Zhang, K. P. Dere, R. A. Howard (NRL), and V. Bothmer (MPI, Germany) have identified the 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 using the Large-Angle and Spectrometric Coronagraph (LASCO) and the Extreme-ultraviolet Imaging Telescope (EIT) instruments on the SOHO spacecraft. They find 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 (15%) of the 27 events are associated with partial halo gradual CMEs emerging from the east limb. Zhang and his collaborators believe that the CMEs are longitudinally extended, having a component moving along the Sun-Earth connection line. One of the 27 major geomagnetic storms was caused by a Co-rotating Interaction Region. They find an asymmetry in the longitudinal distribution of solar source regions for the CMEs responsible for major geomagnetic storms. The average transit time for a solar CME to arrive at the near-Earth space is found to be 64 hours, while it takes 78 hours on average to reach the peak of the geomagnetic storm. The results will appear in the Astrophysical Journal.

3. BLACK HOLE & NEUTRON STAR ACCRETION

Menas Kafatos and Prasad Subramanian (IUCAA, India) are examining scenarios of black hole inner disk instabilities as a possible origin for plasmoid ejection from active galactic nuclei. The inherent assumptions are that the intrinsic AGN variabilities are tied to disk instabilities and that perhaps the plasmoid ejection is also tied to these instabilities. They are looking at how the viscosity can play a role in the overall process.

Peter Becker and graduate student Truong Le have continued to study the physical processes operative in viscous accretion disks surrounding non-rotating black holes. Their most recent work (Becker and Le 2003) has focused on a rigorous determination of the inner boundary conditions for advection-dominated accretion disks. General relativistic effects are included by utilizing the pseudo-Newtonian potential. In their latest work, they are analyzing the possible effect of a shock in the disk on the acceleration of relativistic particles that may escape from the disk to form a wind or jet. The model also self-consistently accounts for the structure of the disk.

Lev Titarchuk, Charles Bradshaw, and Kent Wood have presented a method for determining the B-field around neutron stars based on observed kilohertz and viscous quasi-

periodic oscillation (QPO) frequencies used in combination with the best-fit optical depth and temperature of a Comptonization model. In the framework of the transition layer QPO model, they analyze the magnetoacoustic wave (MAW) formation in the layer between a neutron star surface and the inner edge of a Keplerian disk. They derive formulas for the MAW frequencies for different regimes of radial transition layer oscillations. Titarchuk and his collaborators demonstrate that their model can utilize the QPO as a new kind of probe to determine the magnetic field strengths for 4U 1728-42, GX 340+0, and Scorpius X-1 in the zone where the QPOs occur. Observations indicate that the dependence of the viscous frequency on the Keplerian frequency is closely related to the inferred dependence of the MAW frequency on the Keplerian frequency for a dipole magnetic field. The MAW dependence is based on a single parameter, the magnetic moment of the star, as estimated from the field strength in the transition layer. The best-fit magnetic moment parameter is about $(0.5-1)\times 10^{25}$ G cm for all studied sources. From observational data, the magnetic fields within distances less than 20 km from the neutron star for all three sources are strongly constrained to be dipole fields with the strengths of 10(7)-10(8) G on the neutron star surface.

Titarchuk and Laurent demonstrated that the X-ray spectrum of a converging inflow (CI) onto a black hole is the sum of a thermal (disk) component and the convolution of some fraction of this component with the Comptonization spread (Green's) function. The latter component is seen as an extended power law at energies much higher than the characteristic energy of the soft photons. They show that the high-energy photon production (source function) in the CI atmosphere is distributed with the characteristic maximum at about the photon bending radius, 1.5r(s) independently of the seed (soft) photon distribution. We show that high-frequency oscillations of the soft photon source in this region leads to the oscillations of the high-energy part of the spectrum but not of the thermal component. The high-frequency oscillations of the inner region are not significant in the thermal component of the spectrum. They further demonstrate the Doppler and recoil effects (which are responsible for the formation of the CI spectrum) are related to the hard (positive) and soft (negative) time lags between the soft and hard photon energy channels, respectively.

Kent Wood, Lev Titarchuk, Paul Ray, Michael Wolff, and Michael Lovellette (NRL) developed a model that treats the two outbursts as episodic mass deposition at the outer radius of the disk followed by evolution of disk structure according to a diffusion process. We demonstrate that light curves with fast-rise, exponential decay profile are a general consequence of the diffusion process. Deconvolution of the light curve proves to be feasible and gives an input function specifying mass deposition at the outer disk edge as well as the total mass of the disk, both as functions of time. The derived evolution of total disk mass can be correlated with the observed evolution of the similar to 0.1 Hz QPO in the source reported by Wood *et al.*

Lev Titarchuk and graduate student Nick Shaposhnikov have studied the spectral and temporal properties of three type I X-ray bursts observed from Cygnus X-2 with the Rossi X-Ray Timing Explorer. Despite the short time durations (~ 5 s), these bursts show a radial expansion on the order of several neutron star (NS) radii. We apply the analytical models of spectral formation during the expansion and contraction stages to derive the physical conditions for the matter in the burning zone close to the surface of the NS as well as to derive the NS's mass-radius relation. Their results, combined with statistical errors, show that the central object is a compact star with a mass of 1.4 solar masses and a radius of ~ 9 km. These results favor the softer equation of state for NS matter.

Lev Titarchuk has presented 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 using half-width of the QPO feature. Taking into account this effect, Titarchuk has 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 an invariant quantity, an inclination angle of the magnetospheric axis with respect to the normal to the disk. Titarchuk shows that the inferred values for this angle are in the range between 5.5 and 6.5 degrees. He concludes that the TLM seems to be compatible with the data.

4. RADIATION HYDRODYNAMICS

Lev Titarchuk and graduate student Nick Shaposhnikov have presented an analytical theory of thermonuclear X-ray burst atmosphere structure. Newtonian gravity and the standard diffusion approximation are assumed. Hydrodynamic and thermodynamic profiles are obtained as a numerical solution of the Cauchy problem for the first-order ordinary differential equation. They further elaborate a combined approach to the radiative transfer problem that yields the spectrum of the expansion stage of X-ray bursts in an analytical form in which Comptonization and free-free absorption-emission processes are accounted for. A relaxation method on an energy opacity grid is used to simulate a radiative diffusion process in order to match the analytical form of the spectrum, which contains the free parameter, to the energy axis. Numerical and analytical results show strong similarity. All spectra consist of a power-law soft component and a diluted blackbody hard tail. They derive simple approximation formulae suitable for mass-radius determination by observational spectral fitting.

5. EXTRAGALACTIC ASTRONOMY & COSMOLOGY

Sisir Roy and Menas Kafatos have proposed new laboratory experiments using He-Ne lasers to verify the Doppler-like shift of frequency as developed in their theoretical framework. Data for variation of the full width at half maxi-

mum of different spectral lines from quasars as a function of z can be combined with the variation of the number density with z to explore the possibility of multiple scattering in the environment of quasars.

Roy and Kafatos have also revisited the concept of nonlocality as verified in recent laboratory experiments over a distance of 12 km, by considering the non-commutativity of the operators, as well as symmetry breaking. A geometric description (using sheaf cohomology) for EPR nonlocality as well as the Bohm-Aharanov nonlocal correlation has been proposed.

Shobita Satyapal's research efforts focused on an infrared spectroscopic study of ultraluminous infrared galaxies (ULIRGs) and nearby lower luminosity Low Ionization Emission Line Regions (LINER) galaxies. In particular, she found that virtually all of the ULIRGs and LINER galaxies observed by Infrared Space Observatory (ISO) show spectra dramatically different from typical starburst galaxies or AGN: virtually no high excitation lines characteristic of AGN narrow line regions are detected in the mid-IR and low excitation far-IR spectra are observed. In collaboration with M. Luhman (IDA), J. Fischer (NRL) and others, Satyapal conducted a [CII] 158 micron survey of 15 ULIRGs showing that, relative to the far-infrared (FIR) dust continuum, the [CII] flux from ULIGs is 10% of that seen from nearby normal and starburst galaxies. This result could have important implications for the usefulness of the [CII] line as an eventual tracer of high-redshift protogalaxies, which may resemble the disturbed ULIGs at low redshift observed in this study.

In an effort to better understand the central energy sources in LINER galaxies, Satyapal initiated a multiwavelength study of nearby infrared-bright LINER galaxies. Graduate student Rachel Dudik analyzed archival mid-infrared spectroscopic observations of all 26 LINER galaxies observed by ISO; undergraduate student Mona Sanei analyzed the far-infrared spectroscopic observations of all 40 LINERs in the ISO archive; and undergraduate John McNulty (SJU), in collaboration with Rita Sambruna, analyzed the X-ray archival observations from the Chandra X-ray Observatory of the 33 LINER galaxies with joint infrared spectroscopic observations. This project has led to some exciting and unexpected results: 1) In comparison with normal, starburst, and standard AGN, the LINERs display a low excitation far-infrared spectrum with some of the weakest [CII] 158 micron emission yet seen, 2) Less than a quarter of the LINER galaxies observed show strong detections of high excitation mid-IR fine structure line emission characteristic of AGN, 3) X-ray nuclear point sources morphologically consistent with AGN is seen in $>$50% of the sample, and 4) several sources which show strong X-ray nuclear point sources do not show the high excitation lines characteristic of AGN in the mid-infrared. With the advent of SIRTF and other future multiwavelength missions, it is critical to determine why these multiwavelength diagnostics do not result in a self-consistent picture of the dominant energy mechanism in these classes of galaxies.

Rita Sambruna continued her study of relativistic X-ray jets in AGN. All the Chandra and HST observations of the 17 jets of the sample have been acquired and are in the process of being analyzed. It is found that the rate of detection at X-rays and optical of the radio jets is comparable (60-70%). Comparing the multiwavelength morphologies, a variety of situations is apparent, indicating a range of physical conditions. Detailed modeling of the Spectral Energy Distributions (SEDs) is in progress. It is found that inverse Compton scattering of the Cosmic Microwave Background photons is the dominant process responsible for the X-ray emission, implying relativistic bulk motion (Gamma 5) on kiloparsec scales (Sambruna *et al.* 2002).

Together with graduate student Jessica Gambill, Sambruna studied the X-ray spatial and spectral properties of the X-ray cores (Gambill et al. 2002). There is no evidence for diffuse X-ray emission around the nuclei, implying that in these sources (mostly FRIIs), the jets propagate freely. The spectra are generally described by power laws with average photon index 1.7, and no difference between core- and lobe-dominated sources. In one source, evidence for an Fe Kα emission line is found, making this one of the few luminous radio-loud quasars where the line was detected so far.

A study of the ASCA and BeppoSAX spectra of 4 luminous radio-loud AGN was performed by Sambruna together with Micheal Eracleous and undergraduate student Christa Hasenkopf at PSU. The X-ray spectra show the presence of a strong Fe Kα emission line in 3/4 cases, with an Equivalent Width consistent with that of radio-quiet AGN of similar luminosity (Hasenkopf, Sambruna, & Eracleous 2002).

Sambruna, together with S. Gallagher and others at PSU studied the complex X-ray emission of the Ultraluminous IR galaxy Mrk231 with Chandra (Gallagher *et al.* 2002). A heavily absorbed point source, coincident with the nucleus of the galaxy, was detected embedded in diffuse X-ray emisison possibly associated with the starformation region. These data shed further light on the origin of the X-ray emission in ULIRGs.

Sambruna, Gliozzi (GMU), and Eracleous (PSU) analyzed archival RXTE observations of two nearby Broad-Line Radio Galaxies, 3C120 and 3C390.3 (Gliozzi *et al.* 2002). The X-ray data were part of a long multiwavelength monitoring campaign of the two sources, spanning a period of 3 months. Significant long- (weeks) and short- (days) term variability was observed for both sources, but with substantially different behaviors. In 3C390.3, shorter-term flux changes were superposed on a longer-term decay, while in 3C120, the flux flickers on a more rapid timescale. These results were interpreted in the context of an accretion disk + jet model, with the former dominating in 3C390.3 and the latter in 3C120.

6. COMPUTATIONAL ASTROPHYSICS AND DYNAMICAL ASTRONOMY

During the last year, John Wallin worked with Dr. James Higdon (Cornell) to complete a set of preliminary models of the interaction that created the jets in NGC 1097. These interactions model the destruction of a compact spiral as it passes through the disk of a disk dominated spiral that is a thousand times more massive. During the interaction, the rotation of the compact galaxy's disk combined with the

strong tidal forces during the interaction create two narrow streams of stars. These narrow streams evolve into jet-like features that have similar morphology to those in NGC 1097, including the strange dog-leg feature seen in the north-east jet.

Work was also published in the Journal of Computational Physics with GMU students J. Waltz, G. Page, S. Milder, and A. Antunes comparing the the efficiency of K-D and Barnes-Hut trees for gravity calculations and nearest neighbor searches for SPH calculations. BH trees show a decisive advantage for gravity calculations for most test cases considered, while the K-D trees show advantages for nearest neighbor searches.

J. Wallin also worked on formulating Local Polynomial Regression into an ALE framework in multiple dimensions. This system reformates particle-base hydrodynamics in a form similar to edge-based finite element methods with more complex connectivity. It also shows promise for solving hydrodynamical problems with poorly conditioned grids.

The parallel N-body code mass99 being developed by Wallin and students at GMU was tested on the 67-node Beowolf cluster. Although additional optimization is needed, runs with several million particles are now possible.

John Guillory has also taken over the Interplanetary Dust and COBE/DIRBE Data grant (NASA) on the death of Prof. Leonid Ozernoy. Under this program graduate student Russell Youmans has now simulated gravitational orbits for a distribution of comet fragments with distributed 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 JET INTERACTIONS

James Beall has continued to work with Dr. Wlodek Bednarek (Univ. of Lodz, Lodz, Poland) on the gamma-ray emission produced by the interaction of relativistic jets with the broad-line regions in active galaxies. Several blazars emit gamma-ray spectra that could be explained by such a process. This is an extension of their previous work that appeared in the Astrophysical Journal in 1999. Beall and Bednarek are also studying neutrino production in supernova explosions and possible observational implications.

John Guillory, James Beall, and former student Dave Rose (MRC Albuquerque), continue to study the mechanisms by which relativistic jets in active galaxies interact with the ambient medium to produce observable optical signatures. During the past year, they have confirmed, using PIC code simulations, earlier estimates of the expected luminosity of line emission from the jets and shown that the jets can add a significant high-energy tail to the Maxwell-Boltzmann of the ambient gas. Using a modified version of XSTAR (a photoionization code written by Tim Kallman), they have demonstrated how some of the line emission strengths change due to variations in the high-energy tail fraction in the particle distribution.

These results will eventually allow accurate estimatation of the line emission from the broad-line region (BLR) clouds in active galactic nuclei (AGN). Beall, Guillory, and their collaborators intend to compare these computational and analytical results with line emission measures from observations; specifically, the ratio of FeII/Hα, as a test of the photoionization vs. the relativistic jet ionization model for the BLR of AGN.

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