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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 Institute for Computational Sciences and Informatics (CSI) at George Mason University, for the period October 1, 1996 to September 30, 1997. Faculty in the CEOSR program were J. Beall, P. Becker, R. Ellsworth, J. Guillory, P. Hertz, M. Kafatos, K. Olson, L. Ozernoy, M. Summers, L. Titar-chuk, J. Wallin, K. Wood, and R. Yang. Further program information is available at http://www.ceosr.gmu.edu.

1. INTRODUCTION

The interdisciplinary doctoral program in Computational Sciences and Informatics 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 sciences and informatics core; specialty tracks of computationally intensive courses; and doctoral research. CSI maintains active relationships with a number of high-technology corporations in the Washington, D.C. area. CEOSR faculty are involved in many ongoing collaborations with scientists at the Naval Research Laboratory and NASA/Goddard Space Flight Center.

Members of CEOSR have also been active in the Washington Area Astronomers, a regional organization of professional astronomers stretching from Charlottesville to Baltimore. Recent meetings of the WAA have included talks by P. Becker and L. Ozernoy. P. Hertz serves on the Executive Committee. CEOSR will host the Fall 1997 meeting of the WAA in the Johnson Center on 30 October 1997. Recent CSI graduate P. Subramanian and current student G. Marani will report on work performed for their doctoral dissertations. The Local Organizing Committee is composed entirely of CEOSR and CSI members.

2. OBSERVATION ASTRONOMY & MULTIFREQUENCY DATA ANALYSIS

M. Kafatos and student E. Ramos have obtained IUE/EUVE observations of 3C 273 (Ramos, Kafatos, & Fruscione 1996; Ramos *et al.* 1997) as part of the larger EGRET multifrequency observing campaign of 1993-1995 (von Montigny *et al.* 1996). 3C 273 is an interesting blazar because of its prominent UV bump attributed to an underlying accretion disk. E. Ramos developed statistical models to search for significance in the time-series analysis of high-energy emission from 3C 273 as part of his doctoral thesis, completed this year. The EUV observations using the Deep Survey instrument indicate strong evidence for variability at the 99% level. Collaborators in the 3C 273 and Mk 421 campaigns include A. Fruscione (CEA), F. Bruhweiler (CUA), R. Hartman, C. Fichtel and C. von Montigny from the EGRET team (GSFC), T. Courvoisier (Geneva), Y. Kondo (IUE), I. McHardy (Southampton), F. Makino (ISAS), T. Weekes (Whipple), M. Urry (STScI), W. Collmar and G. Lichti (Max Planck–Garching), A. Marscher (BU), H. and M. Aller (UMI), L. Maraschi (Genoa), and S. Wagner (Heidelberg).

In collaboration with J. Higdon (ATCA/ATNF), J. Wallin has continued 21 cm radio observations of several interacting ring galaxies including AM0644-741 and AM1724-622. Infrared and narrow band optical observations are also continuing on selected systems to constrain the local star formation rates. Some of the work on AM0644-741 has recently been reported in the Astrophysical Journal.

Student C. Bradshaw in collaboration with B. Geldzahler and E. Fomalont is continuing astrometric observations to determine the radio parallax of the Low Mass X-ray Binary Scorpius X-1. Observations made with the VLBA at 6 cm set a lower distance limit of 1300 pc. Continuing observations are being made to refine this estimate. Additionally, 1996 observations indicate that the majority of radio flux density from Scorpius X-1 is external to the binary. Two coordinated VLBA and RXTE observations of Scorpius X-1 were made in August 1997 to relate this new radio morphology with the X-ray state.

Student J. Lee has continued to analyze data from the Thin Ionization Calorimeter (TIC), which is a balloon-borne cosmic ray experiment to measure the cosmic ray energy spectrum in the energy range from 100 GeV up to 10 TeV. TIC calorimeter consists of five iron plates that have a dimension of 30.5 cm X 30.5 cm with 6 cm thickness. Each plate is followed by a 1.5 cm thick scintillator. TIC has a vertical thickness of 1.95 proton interaction mean free paths (or 17.23 radiation lengths) and a geometric factor for isotropic flux of 1.01 m^2 $ster^{-1}$. Each cosmic ray which hits the calorimeter and deposits sufficient energy creates an event to be processed by the TIC electronics. If there are simultaneous signals from the two PMT's, these signals are fed into amplifiers with two different gains. These outputs are connected to 256-bit ADC and mapped into 14 channels that are quasi-logarithmically spaced. Pulse height spectra measured during the flight will be converted into cosmic ray spectra based on the Monte Carlo simulations.

3. BLACK HOLE ACCRETION

P. Subramanian, P. Becker, and M. Kafatos have continued to study the physical processes operative in viscous accretion disks surrounding rotating and non-rotating black holes. This work includes the analysis of a new kind of viscosity mechanism in hot, two-temperature disks. The viscosity arises from collisions between ions and kinks in the tangled magnetic field (Subramanian, Becker, & Kafatos 1996). Over the past year, P. Subramanian has focused on the shear-induced Fermi acceleration of relativistic protons in the same scenario, due to collisions with the magnetic scattering centers (kinks) embedded in the Keplerian flow. This work was reported in his doctoral thesis, which was completed this year. It was verified that the total amount of heating due to Fermi acceleration is equal to the traditional viscous heating as expected. The relativistic protons accelerated in the flow are postulated to feed a magnetically collimated jet, leading to the production of a strong γ-ray flux when the jet collides with a distant cloud, possibly in the broad line region within one parsec of the central source. The calculations are relevant for simulations of accretion disks around compact objects, which are expected to have near-equipartition tangled magnetic fields embedded in them. Subramanian, Becker, & Kafatos (1996) applied the hybrid viscosity mechanism to a steady-state model of a two-temperature quasi-Keplerian accretion disk. The values of the α parameter arising from this mechanism fall in the range $0.01 \lesssim \alpha \lesssim 0.5$. They find the viscosity to be influenced both by the degree to which the magnetic field is tangled and by the relative accretion rate $\dot{M}/M$, where M is the black hole mass. Their work has direct consequences for unified AGN models (Kafatos, Ramos, Becker, Subramanian & Yang 1996) involving jets and accretion disks.

M. Kafatos (1996a) proposed a new MHD outflow model to explain the observed properties of the jets in the binary system symbiotics R Aquarii and CH Cygni. In the R Aquarii model, a thick accretion disk ends $\sim 5 \times 10^{11}$cm from the hot companion. Inside this region a magnetosphere dominates. A slow wind (~ 100 kms^{-1}) emanates from the outer accretion disk, perhaps driven by radiation pressure on grains. High-velocity jets would not be seen in this picture. In contrast, CH Cyg possesses a disk terminating at radius $\sim 10^{10}$cm, and in this case a high-speed jet can form in the vicinity of the hot star with escape speeds $\sim 1{,}000$ kms^{-1}. Hollis, Pedelty, & Kafatos (1997) examined the parameters of a lateral shock in R Aquarii. In conjuction with a proper motion analysis of the jet material, they evaluate the observational results in terms of a schematic model in which the jet emission consists of plane-parallel isothermal shocks along the leading edge of rotation.

L. Titarchuk, A. Mastichiadis, N. Kylafis, and Th. Zannias formulated and solved the problem of spectral formation in steady state, spherical accretion flows onto black holes. They claim that observation of an extended power law up to 511 keV, formed as a result of bulk motion Comptonization, provides firm observational evidence for the existence of the underlying black hole. L. Titarchuk and A. Muslimov explained the set of QPO frequencies and the peak spacing in the power spectra of millisecond variability detected by RXTE in the X-ray emission from LMXB in terms of the rotational splitting (due to the Coriolis force) of an intrinsic frequency caused by an accretion disk. They calculated this effect and demonstrated that there is a striking agreement with the observational data.

4. RADIATION HYDRODYNAMIC

P. Becker has analyzed the structure of radiative, radiation-dominated shocks in accretion columns over the magnetic poles of bright X-ray pulsars. In pulsar accretion columns, the mass and momentum fluxes are conserved while the gas crosses the shock, but the energy flux is not. The loss of kinetic energy via the diffusion of photons through the walls of the column causes the gas to decelerate to rest at the stellar surface. By contrast, in the standard theory of adiabatic, radiation-dominated shocks developed by Blandford and Payne in 1981, the energy flux is conserved, and the downstream flow velocity cannot vanish. Hence adiabatic shocks have no relevance for X-ray pulsar accretion flows. Becker (1997a) obtained a new, analytical solution for the variation of the flow velocity above the polar cap of the neutron star including the dynamical effect of photon escape. These solutions display the correct ''settling'' character below the sonic point, and the flow velocity vanishes at the stellar surface as required. The new results obtained by Becker therefore provide a much more reasonable description of the accretion process when the flow is confronted by a barrier, such as the solid surface of a neutron star, or the centrifugal ''wall'' surrounding a black hole. Preliminary results based on the mathematical approach developed by Becker (1997b) show that the inclusion of radiative losses in the calculation leads to a substantial hardening of the radiation spectrum. The new model may improve our understanding of the spectral formation mechanisms operative in bright X-ray pulsars.

5. LARGE-SCALE NUMERICAL SIMULATION

J. Wallin constructed numerical models of interacting galaxies in collaboration with K. Olson (GSFC). Gravitational treecodes with Smoothed Particle Hydrodynamics (SPH) have been successful at reproducing most of the large-scale features of specific collisional ring systems. However, problems still remain in predicting the gas densities in specific regions of interacting galaxies. Since the gas is essentially isothermal throughout these systems, the physics seems to be dominated by the artificial viscosity terms in the SPH equations rather than by real hydrodynamics. Investigations of this problem are continuing.

J. Guillory has generalized the concept of computational subcycling of a code in time and/or space, to develop the concept of ''multiscale'' codes, which can extend by many orders of magnitude the effective size and duration that can be correctly simulated in both astrophysical and laboratory plasma problems. In such a code, a master algorithm directs the running of a particle-in-cell module (in certain spatial regions, and at certain times) to obtain microscopic dynamical results that feed information to an MHD or hybrid code module which runs with much coarser space and time steps but cannot otherwise model the microphysics. The master code then feeds coarse-grained information about the local ambient environment to the PIC code as needed. Additional modules, e.g. a surface-interaction and solid response code module, can be similarly directed, exchanging information at selected times and locations with the other program modules.

Using this technique, large scale (many millions of Debye shielding lengths) long-duration (many millions of plasma periods) astrophysical and space plasma problems can be modeled, taking advantage of the wide separation of space and time scales governing the physics. Graduate student M. Bear has been implementing the first of such multiscale codes under the direction of J. Guillory, to simulate plasma etching of silicon and semiconductor sub-micron features on a wafer (of size around 20 cm) in a plasma processing chamber (of size around 50 cm), with the RF sheath (thickness around 2 mm) also simulated. The timescales range from sub-nanosecond up to the 30-minute process time, a far greater range than could be simulated by a PIC-Monte Carlo code alone. The code is running in its pilot form, properly modeling the micron-scale surface-sheath coupling, and executing the needed information exchange among the three modules at the three spatial scale-sizes; it is also now executing the timed subcycling of the modules, with the long-term changes provided to the slowest (hybrid) module by the system based on the ''snapshot'' rate calculations of the finer-timescale modules and the near-periodic repeatability of the process over many RF cycles.

6. INSTRUMENTATION DESIGN AND DEVELOPMENT

P. Becker, M. Black, and K. Wood, along with CSI student A. Jazaeri and Thomas Jefferson High School student A. Morse have analyzed the design for a new type of X-ray telescope based on coded-aperture methods. The design utilizes a number of sub-instruments that provide observations of the X-ray field of view through a banded, ''grid'' transmission pattern. It was demonstrated that this type of system can yield high-accuracy measurements of the angular Fourier components of the incident intensity distribution. When the field of view contains no unresolved sources, direct summation of the (truncated) Fourier series yields an excellent representation of the incident intensity distribution. Conversely, strong oscillatory residuals imply the presence of unresolved (essentially point) sources in the field of view. In such cases the inversion of the Fourier data to obtain the incident intensity distribution can be accomplished using algorithms such as CLEAN, or alternatively using a maximum-entropy approach. The current design effort focuses on one-dimensional observations made through a slit. Later efforts will generalize this restriction so that the full, two-dimensional field of view can be analyzed at one time.

Student B. Graham has developed a Monte Carlo technique for modeling background in space-based γ-ray telescopes. The major background components included in this modeling technique are the diffuse cosmic γ-ray flux, the Earth's atmospheric flux, the decay of nuclei produced by spallation of cosmic rays, trapped protons and their secondaries, the decay of nuclei produced by neutron capture, and the de-excitation of excited states produced by inelastic scattering of neutrons. The method for calculating the nuclear activation and the decay component of the background combines the low Earth orbit proton and neutron enviroment, the spallation cross-sections from Alice91, nuclear decay data from the National Nuclear Data Center's Evaluated Nuclear Structure Data File database, the three-dimensional γ-ray and beta particle transport with Electron Gamma-Ray Shower, version 4. The Monte Carlo code handles the following decay types: electron capture, beta minus, beta plus, meta-stable isotopes, short-lived intermediate states, and isotopes that have branchings to both beta plus and beta minus. Actual background from the HEAO 3 space instrument is used to validate the code. This code has been applied to study a Compton scatter telescope consisting of two large arrays of position sensitive germanium detectors. These simulations quantify the contributions and spectrum of each background component. The background spectrum of this large Compton scatter telescope is used predict its performance in terms of narrow line and continuum sensitivities.

7. STELLAR ASTRONOMY

L. Ozernoy has continued his work on implementation of the relativistic Doppler effect to extract new information from precision Doppler measurements (PDM) of stellar velocities. He has shown that, along with measuring the inclination angle of binary star orbits (an opportunity that he pointed out earlier), PDM separated in time can supply important dynamical information even for solitary stars, especially if the star is located in a dense stellar field, such as a globular cluster. Although a related technique of pulsar timing is used for millisecond pulsars in globular clusters, PDM could open up new opportunities since they deal with optical observations of a much more numerous class of ordinary stars.

L. Ozernoy, jointly with R. Genzel (Max-Planck Inst. für Extraterrestrische Physik, Garching, Germany) and V. Usov (Weizmann Inst., Rehovot, Israel), have analyzed collisions of stellar winds from massive stars in the core of the stellar cluster at the Galactic center. Those wind collisions could result in the production of strong X-ray flares with a rate of $\sim 10^{-4}(N_w/10^3)^2\mathrm{yr}^{-1}$ and a duration ~ 1 week, where N_w is the number of wind-producing stars in the core. Collisions of the stellar winds in the cluster also have a number of other interesting observable implications, including the generation of γ-rays by particles accelerated in shocks from the colliding winds. These processes are also expected to be relevant in compact regions of intense star formation elsewhere.

8. EXTRAGALACTIC ASTRONOMY AND COSMOLOGY

L. Ozernoy has considered collisions between giant molecular clouds (GMCs) in galaxies colliding face-on. According to his analysis, during the time when their central parts cross each other, this process triggers gravitational instability in the bulk of the GMCs located in the central 1-2 kpc of the galaxies, which, in turn, can result in the formation of many so called 'super star clusters' (SSCs). The proposed model explains the basic observational features of SSCs: (i) appearance in irregular and spiral galaxies of all types; (ii) independence of the formation process on metallicity of gas; (iii) a more or less simultaneous formation of $\sim 10^5 - 10^6$ stars in each GMC before the gas as a building material is blown out. An unambiguous signature of the proposed model is that the ages of globular clusters in a given galaxy would reveal a distribution in the form of discrete peaks (each related to the respected collision of the parent galaxy) rather than be distributed continuously. The GMC collision mechanism could also be responsible for globular cluster formation prior to, or in parallel with, the galaxy formation by collisions of protogalactic clouds considered by Ozernoy (1989).

As a contribution to the discussion in IAU Symposium 168, ''Examining the Big Bang and Diffuse Backround Radiations,'' M. Kafatos (1996b) discussed the challenges faced in observational cosmology which are not found in other branches of physical science: The observer is always part of the system under study and a clean separation cannot occur. A-priori requirements may turn out to be part of the observing process itself. Kafatos (1997) examined a number of observational and theoretical concepts in support of the view that non-locality may be a fundamental property of the universe. In particular, he discussed quantum experiments that reveal spatial and temporal non-localities, and explored some consequences of Eddington's and Dirac's observations of certain numerical coincidences involving various physical constants.

9. GAMMA-RAY BURSTS

Student G. Marani has been working under the supervision of R. Nemiroff (Michigan Technological University). Her work involves analysis and simulations of BATSE gamma-ray burst (GRB) data sets, in order to probe the GRB cosmological origin. She has carried out 2-D angular cross-correlations between GRBs and Abell clusters of galaxies, using a novel methodology (Marani *et al.* 1997a). The results confirmed previous claims of a positive correlation, but appeared at least in part to be due to statistical fluctuation. She has also developed computational tools to search for statistical similarities and gravitational lensing events in the GRB time histories (Marani *et al.* 1997b; 1997c). The results of such searches have provided new limits on the maximum distance to the GRBs and the cosmological abundance of dark matter in the form of compact objects.

L. Ozernoy, jointly with V. Dokuchaev and Yu. Eroshenko (Inst. for Nucl. Research, Moscow) further developed their new cosmological scenario of gamma-ray burst (GRB) origin, which envisions the production of GRBs in dense galactic nuclei at the advanced stages of their evolution. The authors have shown that, in the process of a central massive black hole (MBH) formation in an evolved galactic nucleus, the latter becomes a source of *multiple*, or fast recurrent GRBs. As a result of radiative (via gravitational radiation) captures of neutron stars (NSs) from the halo, a very dense temporary cusp consisting of NSs forms near the growing MBH. In the cusp, mutual collisions of NSs occur mainly through radiative captures of two NSs into a binary that rapidly evolves and ends up in the merging of the components thereby producing GRBs. Unless the four GRBs on October 27-29, 1996 detected by BATSE from a particular direction on the sky are simply one long event, the proposed model is able to explain such a recurrency.

10. SOLAR SYSTEM & INTERPLANETARY DUST

L. Ozernoy, jointly with N. Gor'kavyi and T. Taidakova (Crimean Astrophys. Obs., Ukraine) and J. Mather (GSFC/NASA), have extended further their novel approach to interplanetary dust dynamics, which is based on the use of the kinetic equation for the particle density in the space of orbital coordinates and combines analytical and hydrodynamical methods in conjunction with celestial mechanics orbit calculations and numerical computations. The authors improved their 'reference model' (that describes the 3-D structure of the zodiacal cloud produced by 5000 asteroids and 217 comets) by including those $\sim 10\%$ of particles which are subjected to resonant effects. For resonant line $a=$const in the (a,e)-space, where a is the major semiaxis and e is the eccentricity, the authors solve analytically the transport equation and then compute the (a,e)-distribution of resonant particles for dozen of different resonances with the planets. With the use of the new transformation techniques to the (R,Z)-space (R being heliocentric distance and Z being geocentric altitude), the structure of the dust resonant ring near Earth has been computed.

11. RELATIVISTIC JET INTERACTIONS

J. Beall and J. Guillory continue their investigation of 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 via plasma (collective) processes. This work has expanded to include a collaboration with D. Rose, who recently completed his Ph.D. in the CSI program under the direction of J. Guillory, and has become a Research Affiliate at CSI.

The research undertaken by Beall, Guillory, and Rose comprises an interdisciplinary project of substantial proportions, and applies an understanding of the elements of plasma physics to the interaction of an ambient medium with highly-collimated jets of material emitted from the cores of some (and perhaps all) AGNs and quasars (QSOs).

The research by Beall and Guillory uses a computer code that solves a time-dependent system of extremely stiff, coupled, differential equations. These model the intensity of plasma waves generated by the propagation of the (relativistic) jet as it travels through the ambient medium at the core of the active galaxy. This medium is likely to include the Broad and Narrow Line Regions (BLR and NLR) that contribute the bulk of the line emission from these objects.

X-ray and γ-ray observations of AGN suggest that the observed fluxes are produced by the interaction of the jet with the ambient medium. This in turn suggests that at least for some AGN, the kinetic luminosity of the jets must be a significant fraction of the total luminosity of the object. Thus, the interaction of the jet with the ambient medium is expected to have consequences for radiation at other frequencies. This is especially true since the dominant energy loss mechanism for the jets in AGN is via plasma processes, specifically the two-stream and corollary instabilities.

One of the consequences of such a jet, as determined by the research of Beall and Guillory, is the production of a non-thermal, high-energy tail to the Maxwell-Boltzmann distribution of the ambient gas. Beall and Guillory have modified the Kallman and Krolik photoionization code, XSTAR, to estimate the effect of such a hot, non-thermal tail on the emission from a photoionized cloud with parameters consistent with those of the BLR. Their work shows that the jet can significantly change the emitted spectrum of the BLR clouds, especially in the UV and EUV regions of the electromagnetic spectrum. Estimates of the parameters of the BLR and NLR clouds obtained without taking these effects into account can thus be in error by orders of magnitude.

The collaboration with D. Rose uses a PIC (Particle-in-Cell) code to benchmark the original (so-called zero-dimensional) computer code to test some of the physical assumptions in it. The 2- and 3-Dimensional PIC codes are sufficiently computationally intensive that it becomes impractical to apply them to the parameter ranges relevant for AGNs and QSOs. Benchmarking is therefore an essential element in the progress that can be made in this area. The PIC-code calculations confirm the essential features of the zero-dimension code, including beam propagation length, inter-penetration of the jet and the ambient medium, and production of a non-thermal tail on the Maxwell-Boltzmann distribution of the electrons in the ambient medium. This non-thermal tail collisionally ionizes the ambient medium.

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