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, 1999 to September 30, 2000. Faculty and postdocs in the CEOSR program were J. Beall, P. Becker, R. Ellsworth, J. Guillory, P. Hertz, M. Kafatos, K. Olson, L. Ozernoy, P. Subramanian, M. Summers, L. Titarchuk, A. Vourlidas, J. Wallin, K. Wood, and R. Yang. S. Roy was a visiting faculty member. Further program information is available at http://www.ceosr.gmu.edu.

1. INTRODUCTION

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 sciences and informatics core; specialty tracks of computational intensive 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

Menas Kafatos and a number of researchers from several institutions (Malabika Roy, visiting scientist, GMU; Elio Ramos, Univ. Of Puerto Rico/Mumacao; Joseph Papadakis, John Papamastorakis and Kanaris Tsinganos, Univ. of Crete; and Rita Sambruna, Penn State and now at GMU) have been studying the multifrequency observations of the peculiar BL Lac object AO 0235 and conducting their own observations using the 1 meter telescope in Crete. Cross-correlation analysis using statistical methods have been utilized. In particular, they studied the high and low states of the blazar and find correlated fluxes between optical and radio wavelengths. They also find periodic variations at radio frequencies which may indicate a dynamo effect in the jet or, alternatively, the presence of a hot spot in an accretion disk.

Angelos Vourlidas worked under contract at the Large Angle and Spectroscopic Coronagraph (LASCO) project which is flown aboard the Solar Heliospheric Observatory (SOHO) satellite. LASCO is a Navy Research Laboratory (NRL) project and therefore he is stationed at NRL. His responsibilities at NRL include research and data analysis in support of LASCO. During the past year, he continued his work on the energetics of CMEs observed by LASCO in collaboration with the UVCS team and the Nancay radioheliograph group. He also investigated the association of CMEs and type-II radio bursts in a series of papers with Drs. Leblanc and Dulk. He provided user/calibration/software support for the daily operations of the LASCO instrument. As the project scientist of the NRL VAULT sounding rocket payload, Vourlidas supervised the refurbishing and preparation of the payload for its second flight in early 2002. He was also involved in the phase-A studies of the SECCHI/COR2 coronagraph to be flown aboard the NASA STEREO spacecraft in 2004. He is currently one of the COR2 instrument managers.

3. BLACK HOLE & NEUTRON STAR ACCRETION

Lev Titarchuk and Vladimir Osherovich suggested that persistent low-frequency quasi-periodic oscillations (QPOs) detected in the black hole (BH) sources XTE J1118+480, GRO J1655-40 LMC X-1 at ~0.1 Hz, and QPOs in HZ Her/Her X-1 at ~0.05 Hz and in neutron star (NS) binaries 4U 1323-62, 4U 1746-31 and EXO 0748-76 at ~1 Hz are caused by the global disk oscillations in the direction normal to the disk (normal mode). They argue that these disk oscillations are a result of the gravitational interaction between the central compact object and the disk. A small displacement of the disk from the equatorial plane results in a linear gravitational restoring force opposite to this displacement. Their analysis shows that the frequency of this mode is a function of the mass of the central object and it also depends on the inner and outer radii of the disk which in turn are related to the rotation period of the binary system.

Philippe Laurent and Lev Titarchuk argue that the recent observations of black hole binary systems show more and more clearly that the observed spectra of these systems result from the Comptonization of the high energy electrons close to the black hole on the ambient soft photons. So, in order to model these observed spectra, one has to treat as precisely as possible the Comptonization process, taking into account the real motion of the electrons, which is, in fact, a composition of their free-falling motion onto the black hole and of their brownian motion due to the electron temperature. While the effect of thermal Comptonization has been already explored in detail, the implications of the free-fall motion of the electrons on the resulting Comptonized spectrum is not yet clearly understood. Also, the general relativistic effects close to the black hole were not yet plainly taken into account.
They present the study of these effects by using a Monte-Carlo simulation which takes into account the exact motion of the Comptonizing electrons, in a fully general relativistic treatment. Some of the results of this study have been presented, and they provide a new insight into the understanding of black hole binary spectral states.

Lev Titarchuk and Vladimir Osherovich show that the recently formulated two-oscillator (TO) model interprets the lowest of the kilohertz frequencies of the twin-peak quasi-periodic oscillations in X-ray binaries as the Keplerian frequency. The high twin frequency in this model holds the upper hybrid frequency relation to the rotational frequency of the neutron star’s magnetosphere. The first oscillator in the TO model allows one to interpret the horizontal branch observed below 100 Hz as the lower mode of the Keplerian oscillator under the influence of the Coriolis force. For some stars such as 4U 0614+09, Scorpius X-1, and 4U 1702-42, all aforementioned frequencies have been observed simultaneously, thus providing the opportunity to check the central prediction of the TO model for a particular source. Given the considerable variation of each of these three frequencies, the existence of an observational invariant with a clear physical interpretation as a global parameter of the neutron star magnetosphere is an important test of the TO model.

Lev Titarchuk and Philippe Laurent present analytical calculations and Monte-Carlo simulations of the specific features of X-ray spectra formed as a result of upscattering of the soft (disk) photons in the converging inflow (CI) into the black hole. The full relativistic treatment has been implemented to reproduce these spectra. They show that spectra in the soft state of black hole systems (BHS) can be described as the sum of a thermal (disk) component and the convolution of some fraction of this component with the CI upscattering spread (Greens) function. The latter boosted photon component is seen as an extended power-law at energies much higher than the characteristic energy of the soft photons. They demonstrate the stability of the power spectral index over a wide range of the plasma temperature 0 - 10 keV and mass accretion rates (higher than 3 in Eddington units). They also demonstrate that the sharp high energy cutoffs occur at energies of 200-400 keV which are related to the average energy of electrons $m_e c^2$ impinging upon the event horizon. The spectrum is practically identical to the standard thermal Comptonization spectrum when the CI plasma temperature is $\sim 50$ keV (typical for the hard state of BHS). In this case one can see the effect of the bulk motion only at high energies where there is an excess in the CI spectrum with respect to the pure thermal spectrum. Furthermore, the effect of the bulk Comptonization compared to the thermal Comptonization is strongest when the plasma temperature drops below 10 keV. They clearly demonstrate that the spectrum emerging from the converging inflow is an inevitable stamp of the BHS where the strong gravitational field dominates the pressure forces.

Prasad Subramanian, Peter Becker, and Demos Kazanas (NASA/GSFC) have continued to study the physical processes operative in viscous accretion disks surrounding rotating and non-rotating black holes. The most recent work has focused on generalization of the ADIOS model of Blandford & Begelman to include the effect of general relativity. This is done by replacing the Newtonian potential used in ADIOS with a pseudo-Newtonian potential. The resulting model displays a relativistic outflow emanating from just outside the radius of marginal stability. They speculate that the outflow may be powered by the shear-induced Fermi acceleration of relativistic protons, due to collisions with the magnetic scattering centers (kinks) embedded in the Keplerian flow. The relativistic protons accelerated in the flow are postulated to feed a magnetically collimated jet, leading to the production of a strong gamma-ray flux when the jet collides with a distant cloud, possibly in the broad line region within one parsec of the central source.

4. RADIATION HYDRODYNAMICS

During the last year, John Wallin was on sabbatical leave at Los Alamos National Laboratory working with the hydrodynamic methods group. During his leave, he investigated a new approach to galaxy simulations which takes advantage of recent developments in meshless methods. Specifically, he worked on Moving Least Squares Particle Hydrodynamics (MLSPH) and Local Polynomial Regression (LPR) as alternatives to using Smoothed Particle Hydrodynamics (SPH).

The direction of this work is twofold. First, methods to improve the consistency of SPH are being examined. Second, methods to eliminate artificial viscosity are being explored, including the use of flux limiters. It is hoped that this work will greatly improve the convergence rates of SPH in a number of astronomical applications. Although this work is still underway, its application should eliminate two serious problems with SPH. First, it has a higher-order consistency making it possible to better approximate complex fields using fewer particles. Second, it does not rely on artificial viscosity to model shocks, making it possible to robustly model complex interactions without tuning parameters.

5. COSMIC RAY ACCELERATION

Peter Becker and Demos Kazanas (NASA/GSFC) have studied the acceleration of cosmic rays due to repeated scattering across a supernova-powered shock wave, using the "two-fluid" model of diffusive shock acceleration. This scenario remains an attractive model for the production of very energetic cosmic rays. When the acceleration process is efficient, a large fraction of the incident gas momentum flux is converted into cosmic ray pressure. In this case, the dynamical structure of the shock must be treated self-consistently, including the modifications due to the cosmic ray pressure. The upstream boundary conditions are stated in terms of the incident total Mach number and the incident ratio of the cosmic-ray pressure divided by the total pressure. It is well known that for certain combinations of these two parameters, 1, 2, or 3 distinct solutions are can be found for the shock structure. However, the precise nature of the constraint curves in the parameter space describing the number of possible solutions for given upstream conditions has remained unclear. Becker and Kazanas (2000) have derived new, exact critical constraints by reformulating the upstream conditions.
in terms of the two individual Mach numbers defined with respect to the cosmic-ray and gas sound speeds. Their results allow for the first time a systematic understanding of the parameter space and the implications for the resulting shock structure.

Peter Becker, Demos Kazanas, and student Truong Le have extended the analysis of the two-fluid model to explore the conditions under which multiple solutions are possible. They propose a new entropy-based method as a discriminant between the various steady-state solutions, when multiple solutions are possible. In the new method, the entropy of the combined gas/cosmic-ray system is computed. Application of the second law of thermodynamics then allows the identification of the most stable solution as that possessing the highest total entropy.

6. EXTRAGALACTIC ASTRONOMY & COSMOLOGY

Menas Kafatos (GMU) and Sisir Roy (Indian Statistical Institute, Calcutta and visiting scientist, GMU) have been studying alternate theories of redshift formation. The frequency shift of spectral lines from astronomical objects is often explained by the Doppler effect and the broadening mainly depends on the temperature in the gas. The Wolf effect, on the other hand, deals with correlation-induced spectral change and explains both the broadening and shift of the spectral lines. In this framework, the width of the spectral line is related to the redshift $z$. In certain cases the shift is larger than the width of the broadening. Also, for small values of $z$, a Tully-Fisher type of relationship can be derived.

Menas Kafatos, Sisir Roy (Indian Statistical Institute, Calcutta and visiting scientist, GMU) and Richard Amoroso (The Noetic Institute) have been studying the cosmological coincidences described by Dirac and others. By deriving numerical ratios, they find certain scale invariant relationships which point to alternate views of time where the constants themselves change and this produces the appearance of an evolutionary universe.

L. Ozernoy has analyzed one of the most intriguing cases of closely associated objects having discordant redshifts, which is represented by the galaxy NGC 4319 ($z = 0.006$) and a peculiar object Mrk 205 ($z = 0.07$) located just 40' away. He has proposed to explain the luminous connection extending from Mrk 205 into the galactic nucleus as well as a corresponding feature on the opposite side of the disk linking the nucleus with a bright UV knot (Sulentic & Arp 1987) in terms of an explosive ejection of both objects from the nucleus with a relativistic velocity. According to this interpretation, the redshift of Mrk 205 includes (i) a receding component, $z_r = 0.065$, due to the transverse Doppler effect and (ii) a cosmological component, $z_c = 0.006$. The velocity of ejection and the angle between the direction of ejection and the line of sight are found to be $v_{ej}/c = 0.261$ and $\theta = 76.3^\circ$, respectively. The proposed interpretation has a number of testable consequences, including the decisive test: Mrk 205 is expected to have an annual proper motion of $\geq 0.8/(D/20\text{Mpc})^{-1}$ milliarcsec, which could be measured at radio wavelengths for the unresolved radio counterpart. If confirmed, this model would indicate that some pairs of quasar-like sources aligned with galaxies represent relativistic ejecta from the galactic nuclei, and therefore redshifts of those sources include a substantial component produced by the transverse Doppler effect.

7. COMPUTATIONAL ASTROPHYSICS & DYNAMICAL ASTRONOMY

L. Ozernoy, N. Gorkavyi, & Taidakova (2000) and N. Gorkavyi, L. Ozernoy, J. Mather, & Taidakova (2000) modified an implicit second-order integrator (Taidakova 1997) to explore the dynamics of a dissipationless system (sources of dust) as well as a dissipative system (dust grains). The integrator provides the necessary stability and accuracy of computations on a time scale of $0.5 \cdot 10^9$ years.

L. Ozernoy, jointly with N. Gorkavyi, J. Mather (NASA/GSFC), and T. Taidakova (CCS) have continued development of a new numerical approach to the dynamics of minor bodies and dust particles, which enables one to increase, without using a supercomputer, the number of particle positions employed in each model up to $10^{10} - 10^{11}$, a factor of $10^9 - 10^7$ higher than existing numerical simulations. They applied this powerful approach, which incorporates all relevant physical processes, to the high-resolution modeling of the structure and dynamics of cometary populations and dust in the Solar system as well as to studying the structure and emission of circumstellar dust disks containing exo-solar planets.

8. SOLAR SYSTEM & INTERPLANETARY DUST

In an invited talk at the IAU Symposium No. 204 “The Extragalactic Infrared Background and Its Cosmological Implications,” L. Ozernoy has reviewed an extensive work done in collaboration with N. Gorkavyi (NRC/NAS), J. Mather (NASA/GSFC), and T. Taidakova (CCS), which aimed at the physical modelling of the interplanetary dust (IPD) cloud in the Solar system, i.e., establishing a link between the observable characteristics of the zodiacal cloud and the dynamical and physical properties of the parent minor bodies. Their computational approach integrates the trajectories of hundreds of particles, which provides a high-fidelity 3D distribution of the dust. Their numerical code accounts for the major dynamical effects that govern the motion of IPD particles: the Poynting-Robertson (P-R) drag and solar wind drag; the solar radiation pressure; particle evaporation; gravitational scattering by the planets; and the influence of mean-motion resonances. The incorporation of secular resonances and collisions of dust particles (both mutual and with interstellar dust) is underway.

L. Ozernoy, N. Gorkavyi, & Taidakova (2000) continued their numerical simulations of the structure of cometary populations between Neptune and Jupiter, both in phase space, i.e., in the space of orbital coordinates $\{a,e,i\}$, and in real space. To this end, they simulated a stationary distribution of comets, which results from the gravitational scattering of the Kuiper belt objects. The objects start from the Kuiper belt and are typically traced until the bulk of comets...
(~90%) are ejected from the Solar system (this happens on a time scale of ~0.5 Gyrs). The influence of all eight planets as well as the effects of mean motion resonances have been taken into consideration. By studying the distributions of comets in semimajor axis, eccentricity, pericenter, and apo-center distances, several interesting features in these distributions have been revealed. The most remarkable ones include: (i) each giant planet dynamically controls a cometary population that has been called the ‘cometary belt’; and, (ii) comets avoid the resonant orbits. The simulated belts maintain the gaps in the (a, e)- and (a, i)-space similar to the Kirkwood gaps in the main asteroid belt.

In another work, N. Gorkavyi, L. Ozernoy, J. Mather, & Taidakova have performed extensive numerical simulations to examine the structure of the dust cloud in the Solar system between 0.5 and 100 AU produced by the Kuiper belt objects. Their simulations offer a 3-D physical model of the ‘kuiperoidal’ dust cloud. Three major components of dust populations have been revealed: (i) ‘freely’ drifting particles, (ii) gravitationally scattered particles, and (iii) particles captured into resonances. In the phase space, the dust distribution has been found to be highly non-uniform: most of the dust is concentrated into the four belts associated with the orbits of the four giant planets, with the Neptune dust belt being the most dense and extended. As distinct from the simulated cometary belts, for which the dominating gravitational scattering results in avoidance of resonant orbits by comets, the dust belts, due to an additional factor – the Poynting-Robertson drag – reveal a rich and complex resonant structure of captured particles.

L. Ozernoy, N. Gorkavyi, J. Mather, and T. Taidakova continued their numerical simulations of the resonant structure in circumstellar dust disks induced by the presence of planets. More than 200 model disks have been computed to learn the effects of various resonances and their relation to the mass of a planet, the initial orbital characteristics of dust particles and particle size, as well as the stellar luminosity and mass. The planet embedded in the disk produces, via resonances and gravitational scattering, (i) a central cavity, or ‘hole’, void of dust; (ii) an off-center cavity or a few cavities; and (iii) an asymmetric resonant dust belt with one, two, or more clumps. These features can serve as indicators of planet(s) embedded in the circumstellar dust disk and, moreover, can be used to determine the mass of the planet and even some of its orbital parameters. The results of this study reveal a remarkable similarity with various types of highly asymmetric circumstellar disks observed with the JCMT around Epsilon Eridani and Vega. The crucial test of the above picture would be the discovery of revolution of the resonant asymmetric structure around the star. For circumstellar disks in ε Eri and Vega the asymmetric design is expected to revolve by, respectively, (0.6 ± 0.8)° and (1.2 ± 1.6)° annually.

9. RELATIVISTIC JET INTERACTIONS

J. H. Beall and J. Guillory continue their collaboration with D. V. Rose, investigating the physics governing the propagation of jets of material originating in the centers of Active Galaxies (AGN), moving outward, and interacting with ambient material in the broad-line and narrow-line regions (BLR and NLR) of AGN. It is believed that the dominant energy loss mechanisms for such jets is via plasma (collective) processes (see, e.g., Rose et al. 1984 ApJ, 280, 550; Rose et al., 1987 ApJ, 314, 95; and Beall, 1990, Physical Processes in Hot Cosmic Plasmas, Kluwer Academic Publishers: Netherlands, W. Brinkmann, F. Giovannelli, & A. Fabian, eds.). In the regime of parameters likely for astrophysical processes, the research uses a 0-dimensional computer code that solves, time-dependently, a system of extremely stiff, coupled, differential equations. This code models the 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. They have recently completed a series of “benchmark” tests of the 0-dimensional code using 1-dimensional and 2-dimensional Particle-In-Cell (PIC) codes and are preparing a paper with the results of that work.

John Guillory has developed a low-density model for polar plasma flow and synchrotron radiation near a magnetized neutron star, which predicts a rather localized radiation region and magnetic-field-aligned electric fields. Student Truong Le is working toward a higher-density, MHD model for the polar region flow with Peter Becker, to be used to model the production of emission in bright X-ray pulsars.

PUBLICATIONS


Summers, M. E. 1999, “Perspectives in Atmospheric Science: Vertical Couplings,” Science, 284, 1783
Titarchuk, L. G., & Osherovich, V. 1999, “Correlations Between Kilohertz Quasi-Periodic Oscillations and Low-


Peter A. Becker