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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, 1995 to September 30, 1996. Faculty in the CEOSR program were J. Beall, P. Becker, R. Ellsworth, B. Geldzahler, J. Guillory, P. Hertz, M. Kafatos, R. Nemiroff, K. Olson, L. Ozernoy, L. Titarchuk, J. Wallin, K. Wood, and R. Yang. Further program information is available at http://www.ceosr.gmu.edu.

1. INTRODUCTION

The multi-disciplinary 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 faculty are involved in many ongoing collaborations with scientists at the Naval Research Laboratory and NASA/Goddard Space Flight Center. CSI also maintains active relationships with a number of high-technology corporations in the Washington, D.C. area.

2. ULTRAVIOLET ASTRONOMY & MULTIFREQUENCY OBSERVATIONS

M. Kafatos and student E. Ramos have been involved in multifrequency observational campaigns for selected blazars, producing UV results which are part of the campaigns. Specifically, the BL Lac object Mk 421 was observed with IUE as part of a campaign that detected a TeV/X-ray flare (Macomb *et al.* 1995). They have also obtained IUE/EUVE observations of 3C 273 (Ramos, Kafatos & Fruscione 1996) 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. Statistical models are being developed by E. Ramos as part of his doctoral thesis to search for significance in the time-series analysis of high energy emission from 3C 273. The EUV observations using the Deep Survey (DS) 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).

S. R. Meier & M. Kafatos developed a comprehensive study of all far-UV spectra obtained with IUE of the symbiotic star R Aquarii covering a 13-year period (Meier & Kafatos 1995). They obtained a variety of nebular and stellar parameters (such as electron density in the jet components, effective black body temperature of the hot star, etc.) which allow a better understanding of the nature of the hot (unseen) companion to the Mira primary.

3. ACCRETION DISKS

P. Subramanian (student), P. Becker, & M. Kafatos have continued to study the physical processes operative in viscous accretion disks surrounding rotating and non-rotating black holes. A considerable amount of theoretical and computational evidence obtained in recent years strongly suggests the existence of tangled magnetic fields (arising from MHD turbulence) embedded in accretion disks around compact objects. In the past year, Subramanian, Becker, and Kafatos have analyzed a new kind of viscosity mechanism operating in hot, two-temperature disks arising from collisions between ions and kinks in the tangled magnetic field (Subramanian, Becker, & Kafatos 1996).

Their current work focuses 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. As a check, they have 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 gamma-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 (1996b) 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 ($\sim$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$1,000kms^{-1}.

L. Titarchuk has studied Compton upscattering of low-frequency photons in a converging flow of thermal plasma. This involves solving the equation of radiative transfer using both numerical and approximate analytic techniques. The specific case treated is that of spherical, steady state accretion onto neutron stars and into black holes. The inner boundary condition is considered to be either reflective or absorptive, depending on whether the accretion occurs onto a neutron star or into a black hole, respectively. The photons escape diffusively and electron scattering is the dominant source of opacity. It is shown that for accretion into black holes the bulk motion of the converging flow of the accreting gas is more efficient in upscattering photons than thermal Comptonization, provided that the electron temperature in the flow is less than 10 keV. In this case, the spectrum observed at infinity consists of a soft component coming from those input photons which escaped after a few scatterings without any significant energy change and of a power law which extends to high energies and is made up of those photons which undergo significant upscattering. The luminosity of the power law is relatively small compared to that of the soft component. The more reflective the inner boundary is, the flatter the power-law spectrum becomes. The spectral energy power-law index for black-hole accretion is always higher than 1 and it is approximately 1.5 for high accretion rates. It is remarkable that the observed black-hole candidate X-ray sources exhibit similar spectra in their high states.

In related work, L. Titarchuk has found relations between the temporal and spectral properties of radiation Comptonized in extended atmospheres associated with compact accreting sources. He demonstrates that the fluctuation power spectrum density (PSD) imposes constraints on the atmospheric scale and profile. According to these constraints, the slope and low-frequency break of the PSD are related to the Thomson depth τ_0 of the atmosphere and to the radius of its physical size, respectively. Since the energy spectrum of the escaping radiation depends also on τ_0 (and the electron temperature kT_e), the relation between spectral and temporal properties follows. This relation allows for the first time an independent estimate of the accreting matter Thomson depth τ_0.

L. Titarchuk has also compared the analytical Generalized Comptonization model (which takes into account relativistic effects as discussed by Titarchuk 1994 and Titarchuk & Lyubarskij 1995) with Monte Carlo calculations for photon Comptonization by relativistic plasma clouds. He has shown that the new analytical models extend the previous work to a much wider range of plasma temperature and optical depth. In general, the emergent spectrum from a hot plasma cloud depends upon the spectral and spatial distributions of the photon sources as well as on the temperature and geometry of the cloud. Based upon the comparison between the theoretical and Monte Carlo calculations, Titarchuk determines quantitatively a range of plasma geometry parameters and temperatures for which the emergent upscattered spectra are insensitive to the spectral and spatial distributions of the sources. Within this parameter range, the shape of the emergent spectrum depends on only two parameters, namely the plasma temperature and β, a parameter which characterizes the distribution of photon sources over the number of scatterings the source photons undergo before escaping from the plasma cloud.

4. RADIATION HYDRODYNAMICS

P. Becker has continued his study of plane-parallel, radiation-dominated shocks, including modifications due to sources and sinks of radiation. In the past year, he has focused primarily on the effects of energy losses driven by the escape of radiation from the flow. This process may be dynamically important in radiation-dominated accretion columns in X-ray pulsars and also in radiation-dominated accretion disks around black holes. In these environments, the mass and momentum fluxes are conserved while the gas crosses the shock, but the energy flux is not. The ''standard'' theory of plane-parallel, radiation-dominated shocks, developed by Blandford and Payne in 1981, is based upon the assumption of a conserved energy flux, and therefore it cannot be applied with precision in either the neutron star or black hole cases. This has motivated Becker to examine the problem of one-dimensional radiation-dominated flow with a variable energy flux that is allowed to decrease in response to the escape of radiation.

In the standard model (with constant energy flux), the flow velocity can decrease by no more than a factor of 7 as the gas crosses the shock. The downstream gas velocity is therefore always finite, and the flow never displays a ''settling'' character. By contrast, when the energy flux is allowed to decrease in response to radiative losses, the flow actually *stagnates* in the downstream region. 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 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 high-luminosity accretion flows around neutron stars and black holes.

5. GALAXIES AND GALAXY DYNAMICS

In collaboration with J. Higdon (ATCA/ATNF), J. Wallin has continued to work on a number of observational projects focusing on the dynamics and associated star formation processes occurring in interacting galaxies. Work was completed on the star formation rate in AM0644-741 and on the star formation history of AM1354-250, two systems of interacting ring galaxies. HI observations of the ring galaxy system AM1724-622 are being prepared for publication as well.

Radio observations of NGC 1097 were made using the Very Large Array to constrain the origin of the visible ''jets'' seen in deep optical surveys. The lack of 20cm continuum combined with no apparent X-ray, 60cm, or 6cm emission have eliminated the possibility that the observed radio emission is produced via either thermal bremsstrahlung or synchrotron. Interpretation of multiwavelength spectra of the jets has led to the conclusion that these features are actually composed of stars. The unusual distribution of the stars in the jets, combined with their low ages (based on broad-band colors), suggests that they may have formed as a result of a previous tidal encounter or possibly due to interactions with a jet from the LINER nucleus in NGC 1097. Since there is no HI associated with the jets, and there is no likely companion which could have produced a tidal interaction, Wallin and Higdon have concluded that these stars probably formed as the result of in-situ star formation in an aging jet.

6. COSMOLOGY

As a contribution to the discussion in IAU Symposium 168, ''Examining the Big Bang and Diffuse Backround Radiations,'' M. Kafatos (1996a) presented observational 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.

L. Ozernoy and V. Lipunov (Sternberg Astr. Inst., Moscow) have shown that appropriate conditions to accelerate particles to ultra-high energies, up to the Planck energy, exist in the Universe even at very recent epochs in the nuclei of galaxies under certain conditions. Those conditions are met during the last stages of evolution of a supermassive rotating magnetized star – magnetoid, or spinar – before its collapse into a supermassive black hole. At that stage, a potential drop near a magnetoid approaches a value of $\Delta V \simeq c^2 G^{-1/2} \simeq 10^{27}$ volts independent of its mass. A signature of the magnetoid's collapse is a specific pattern of gravitational wave radiation, which could be detected by a space instrument like LISA.

7. STELLAR ASTRONOMY

L. Ozernoy has continued his work on utilizing precision measurements of optical spectra (obtained using a stabilized iodine absorption cell) to determine the transverse velocities of stars. Using the relativistic theory of astronomical reference frames, L. Ozernoy and S. Kopeikin (Nat. Astr. Obs., Tokyo) elaborated the post-Newtonian theory for determining the Keplerian and post-Keplerian parameters of a binary system consisting of a visible (ordinary) star and a compact (dark) companion using precision Doppler measurements . Successive Lorentz transformations and the relativistic equation of light propagation have been applied to establish the exact treatment of the Doppler effect in binary systems, both in special and general relativity.

8. THE MILKY WAY GALAXY

L. Ozernoy has shown that a recent starburst at the Galactic center could have been triggered by a collision between giant molecular clouds within the central few hundred parsecs. The collision scenario makes it possible to explain the origin of the observed counter-rotation of the ensemble of early-type stars in the central one-parsec cluster. This scenario also envisions a large population of compact stellar remnants, such as white dwarfs, neutron stars, and stellar-mass black holes, in the central parsec of the Galaxy.

L. Ozernoy, jointly with V. Lipunov, S. Popov, K. Postnov, and M. Prokhorov (Sternberg Astr. Inst., Moscow) have examined the population synthesis of X-ray sources at the Galactic center by exploring the evolution of massive binary star populations for a nuclear starburst occurring in conditions similar to those at the center of the Milky Way galaxy, on a timescales of 10 Myr. Monte Carlo simulations were applied to the evolution of a large ensemble of binary systems, with proper accounting for the spin evolution of magnetized neutron stars (NSs). The results include the number of X-ray transients (NS + main sequence star), super-accreting black holes (BHs), and binaries consisting of a BH + supergiant, all as functions of time. By 7 Myr after such a starburst, one expects $\approx$ 1 X-ray source with a BH (Cyg X-1 type), $\approx$ 1 SS 433-like source (BH in the regime of super-accretion), and $\approx$ 37 transient sources with a NS, all to be within the central 1 kpc or so. An interesting result that can be considered as a specific starburst feature is that the ratio of the number of systems like SS 433 to the number of X-ray transients is about 1:100, compared to 1:1000, which is characteristic of the average ratio in the galactic field. The ratio of the total number of X-ray sources containing a BH (of Cyg X-1 + SS 433 types) to the number of X-ray transients with NSs turns out to be a sensitive function of the age of the starburst, and its computed value $\approx$ 0.04 is consistent with observations.

L. Ozernoy and R. Genzel (Max-Planck Inst. für Extraterrestrische Physik, Garching) have shown that the wind from IRS 16 and He I stars in the central 1 parsec of the Galaxy is responsible for the peculiar features of accretion onto a putative black hole at the Galactic center. What makes Sgr A ☆ unique is not that it is just underfed but, in addition, that it has a much lower efficiency of accretion and possibly a lower mass, compared to the AGN case.

L. Ozernoy, jointly with A. Fridman, O. Khoruzhii, V. Lyakhovich (Inst. of Astr., Moscow), and L. Blitz (U. of Maryland) have explored possible mechanisms of generation of the ''mini-spiral'' in the innermost parsec of the galaxy. If the putative black hole lies at the center of the dense central cluster, the mechanism of the central spiral arm generation could be over-reflection instability. If the black hole is off-center, the axial asymmetry of the gravitationall potential could serve as a source of exitation for the density wave. In both cases, the comparison of the generated density wave with the observations can serve to constrain the black hole mass.

9. EXTRAGALACTIC ASTRONOMY

L. Ozernoy extended and developed his earlier work on the kinematical model of jets/blobs ejected from AGN relativistically with equal velocities in the opposite directions (Ozernoy, L. M. & Sazonov, V. N., Nature **219**, 467, 1968; Ap. Sp. Sci. **3**, 395, 1969) so as to determine the basic parameters of the model once the redshifts of the two jets/blobs are measured. Recently, the redshifts of two ejecta have been measured, presumably for the first time in an extragalactic object, for the two central blobs in NGC 4258. The above kinematical model yields the inclination angle of the direction for the blob ejection consistent with the geometry of the galaxian disk. The Doppler, and not an intrinsic (such as gravitational) nature of the blob redshifts, as well as the validity of the relativistic model as a whole can be further tested be measuring the following predicted features of purely relativistic origin: (i) arm length asymmetry and (ii) superluminal proper motion. If the blobs observed so far in X-rays and at optical wavelengths have radio counterparts as well, VLA observations could easily reveal their proper motion.

10. GAMMA-RAY BURSTS

L. Ozernoy, jointly with V. Dokuchaev and Yu. Eroshenko (Inst. for Nucl. Research, Moscow) proposed a new cosmological scenario for the origin of gamma-ray bursts (GRB), which envisions the production of GRBs in the evolved galactic nuclei as follows. The abundant compact stellar remnants (CSRs) such as neutron stars (NSs) and stellar mass black holes (BHs), as well as binaries consisting of them, are formed in the central parts of the galactic nuclei. In compact galactic nuclei, random encounters of CSR, which are accompanied by gravitational wave radiation, result in the formation of radiative binaries and in further CSR coalescence, and this would produce a GRB episode. The rate of GRBs per unit comoving volume required to explain the observed GRB phenomenon is found to be fairly consistent with the rate of NS merging in galaxies. The binaries formed by radiative capture in the evolved galactic nuclei are short-lived compared to the age of the Universe.

11. 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 their novel approach to interplanetary dynamics in implementing the continuity equation written in particle's orbital elements as coordinates. They have shown that the continuity equation, along with fast ''jumps'' of particles due to gravitational scattering on the planets, describe successfully ''slow'' processes such as the Pointing-Robertson (P-R) drag. By integrating the continuity equation, they have found two integrals of motion when the P-R drag dominates the dissipative forces in the dust flow. Those integrals of motion, which imply conservation of the particle's flux in the flow under the P-R drag, allow the investigation of basic characteristics of dust flows from all sources in the Solar system (such as asteroids, comets, Kuiper belt, etc.) or in another planetary system. In particular, the authors reproduced the clasical solution $n \propto 1/r$ that represents approximately the overall distribution of dust in the Solar system. They have also investigated the factors that could be responsible for deviations of the power law index in $n \propto r^{-\alpha}$ from $\alpha = 1$: non-uniform distribution of dust sources around the observer, eccentricity of particle orbits, and the change of particle's sizes due to evaporation.

12. RELATIVISTIC JET INTERACTIONS

J. Beall and J. Guillory continued their investigation of the physics governing the propagation of jets of material originating in the centers of AGNs and moving outward to interact with ambient material via plasma (collective) processes. The research has yielded an estimate of the ionization rates and line luminosities of the Broad Line Region (BLR) of AGNs due to excitation processes driven by the interaction between the jet and the ambient plasma.

Because of the energetics of the beams observed in some AGN, the presence of beams or jets is likely to have direct relevance for the energy balance and dynamics of the BLR and NLR. This seems especially true, since the dominant energy loss mechanism in the interaction of relativistic jets with the ambient medium in an AGN will be through plasma processes. One of the consequences of such a jet 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.

J. Guillory and student D. Rose are studying the spatial and temporal dependence of conductivity and magnetic field generation by an energetic baryon jet penetrating into an initially weakly-ionized plasma. One question that this research is answering is: How big is the magnetized region around a thin stream of mass ejection when ejection corresponds to ion acceleration, with electrons ''following?'' Magnetic diffusion into anisotropic conducting plasma has been simulated using the IPROP hybrid code with a time-dependent spatially-averaged ionization model giving sigma. Other applications (besides astrophysics) are to ion-beam driven fusion and ion-beam assisted plasma processing.

J. Guillory and D. Rose are also investigating the space-time dependence of relativistic electron beam penetration into a fully-ionized plasma magnetized transverse to the injection direction using 2D and 3D PIC simulations. This work uses the 3D ARGUS PIC code and the 2D MAGIC PIC code as well as the pseudo-3D version of IPROP.

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