North Carolina State University
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1. REPORT PERIOD

This report covers astronomical and astrophysical research done in the Department of Physics at North Carolina State University from November 1993 through October 1995.

2. PERSONNEL

During the report period, faculty performing research in astrophysics included Drs. John M. Blondin, Kazimierz Borkowski, Donald C. Ellison, and Stephen P. Reynolds. Dr. Borkowski joined the department as a Research Assistant Professor in September 1995. Dr. Jeffrey M. Knerr held a position as a Post-Doctoral Associate until August 1995, when he left to take a position at the University of North Carolina at Greensboro.

During the report period, undergraduate and graduate students carried out research on various projects. C. L. Bennett is completing his work for a Ph. D. degree, carrying out hybrid simulations of particle acceleration in shocks, and has accepted a post-doctoral appointment at UCLA beginning January 1996. D. Dinge, a student at UNC-Chapel Hill, is performing a thesis under the direction of Dr. Blondin. Graduate students G. Double, K. Dyer, M. Owen, and E. Wright have been working in the group as well. Undergraduates making significant contributions included A. Antonelli, T. Coffey, A. Danagoulian, A. Hornschemeier, J. Layton, J. Lyerly, R. Strickland, and the entire membership of the undergraduate class PY 228, Introduction to Astrophysics. Their work is described below.

3. NOTABLE ACTIVITIES

NASA's Astrophysics Theory Program awarded a major grant to the NCSU astrophysics group for research on X-ray emission from supernova remnants (S. Reynolds, PI; J. Blondin and K. Borkowski, co-I's) allowing Dr. Borkowski to join the group from the University of Maryland. Blondin is also supported under the Astrophysics Theory Program (M. Richards, U.Va., co-PI). Other funding sources have included NASA's Space Physics Theory Program (D. Ellison, PI), the NSF's Research Experiences for Undergraduates program, various other NASA programs, and Sigma Xi.

A major international meeting, the Cornelius Lanczos International Centenary Conference, was held December 12–17, 1993. This meeting, jointly sponsored by NCSU's Departments of Mathematics and Physics, commemorated the work of distinguished theoretical physicicst and applied mathematician Cornelius Lanczos with invited and contributed talks in astrophysics, theoretical physics and gravitation, and computational mathematics. Minisymposia on astrophysical topics included numerical MHD and plasma simulations, quantum gravity, black-hole thermodynamics, and galaxy formation and large-scale structure in the universe.

4. INDIVIDUAL RESEARCH

Astrophysical research at NCSU is carried out in the areas of active galactic nuclei (Ellison, Knerr, Reynolds); supernova remnants and the interstellar medium (Blondin, Borkowski, Ellison, Reynolds); shock waves and particle acceleration (Ellison, Knerr, Reynolds); X-ray binaries (Blondin); planetary nebulae (Borkowski); and general computational hydrodynamics (Blondin, Knerr).

4.1 Active Galactic Nuclei

Knerr, with W. Christiansen (UNC-CH) and A. Schiano (UC-Irvine), has been studying the acceleration of cool dense clouds embedded in hot supersonic winds, with applications to broad absorption lines seen in quasar spectra. Hydrodynamic studies clearly indicate that although dense clouds confined and accelerated by ram pressure are indeed subject to the classical instabilities, rapid catastrophic disruption does not occur because of the pseudo-stabilizing effect of continuous ablation of surface structures generated by small-scale instabilities. This form of ablative stabilization requires a large difference between the wind flow velocity and the cloud's internal sound speed so that the surface instabilities can develop incoherently. A major finding in the study is that ablative stability of ram-pressure confined clouds enables the clouds to survive the acceleration process up to velocities at least an order of magnitude greater than their initial internal sound speed.

4.2 Supernova Remnants and the Interstellar Medium

Blondin used numerical hydrodynamic simulations to study the instability of astrophysical shockwaves. With undergraduate student Russell Strickland he studied the overstability of radiative shocks in one and two dimensions. In 1D this work highlighted the dependence of this overstability on both the downstream boundary conditions and on the preshock Mach number (or alternatively, the total downstream compression). In 2D this work illustrated the complex dynamical interactions between the postshock cooling region and the layer of cold, dense gas formed downstream of the shock. In all cases the interface between these two regions was dynamically unstable, at least to nonlinear perturbations. In particular, for low Mach-number shocks, these new instabilities resulted in very large deviations from a planar shock.

With undergraduate student Brian Marks, Blondin studied another shock instability present when a slab of gas is bounded on both sides by isothermal shocks: the Nonlinear Thin-Shell Instability. Using hydrodynamic simulations of a shock-bounded slab of isothermal gas, this research illustrated the complex nonlinear evolution of the NTSI. The presence of the NTSI was confirmed as well as its predicted dependence on wavelength and amplitude, although the instability was observed to choke itself off under some circumstances (but not before the slab had grown in width by two orders of magnitude).

Borkowski, Blondin, and R. McCray (JILA) are studying the expected X-ray emission from, and the dynamics of, the interaction between the supernova blastwave and the circumstellar ring seen around SN1987A. Nonequilibrium-ionization X-ray spectra are being calculated from one and two-dimensional simulations of the shock/ring interaction. Of particular importance is the role of a reflected shock that originates in the first contact of the blastwave with the ring, travels back upstream, reflects off the layer of dense shocked ejecta, and returns to restrike the ring. Particularly in the presence of Rayleigh-Taylor fingers generated in the unstable blastwave, this re-reflected shock can reinvigorate the original shock propagating into the ring, greatly enhancing the X-ray and UV emission. Since this process depends on the geometry of the RT fingers with respect to the ring, we expect this interaction to manifest itself as a ‘‘sparkling’’ of the ring as various RT fingers impact specific points around the ring.

Borkowski continues his work in theoretical interstellar medium research. His current focus is on modeling of X-ray emission from supernova remnants (SNRs). This difficult task requires coupling of multidimensional hydrodynamical simulations with a nonequilibrium plasma X-ray emission code. The calculated X-ray spectra and X-ray morphology are compared with X-ray observations, with particular emphasis on X-ray spectra obtained with the ASCA satellite. This allows for understanding of the SNR dynamics and makes it possible to find the chemical abundances in supernova ejecta.

The famous Cassiopeia A SNR is the first remnant to be studied in such detail. A first attempt at understanding a spatially-integrated ASCA spectrum of this remnant was done under the assumption of spherical symmetry. Borkowski (in collaboration with A. Szymkowiak (NASA/GSFC), Blondin, and C. Sarazin (UVa)) found two distinct components in the Cas A X-ray spectrum: the dense circumstellar shell of material ejected prior to the SN explosion, and the Si- and S-rich SN ejecta. They are continuing work on this remnant, with a particular emphasis on the determination of chemical abundances in the SN ejecta and on the development of hydrodynamical instabilities. They are also investigating how plasma microphysics (such as collisionless electron heating at a shock front and depletion of refractory elements onto dust grains) affects X-ray spectra of SNRs. This is just the beginning of efforts in this direction. The climax will come in several years when the blast wave generated by the SN 1987A hits its famous ring – this newly created supernova remnant will be at the center of astronomers’ attention and will occupy them for decades.

Undergraduate J. Lyerly, with Borkowski and Reynolds, has begun to test Borkowski’s nonequilibrium X-ray plasma code in the context of Sedov SNR dynamics. This work will allow study of the effects on spectral predictions of improved Fe L-shell data in the code. The project will continue by replacing analytic dynamical prescriptions with Blondin’s 2-D hydrodynamic simulations, to study the transition from self-similar driven wave evolution to the Sedov phase in young supernova remnants.

Together with E. Dwek (NASA/GSFC), Borkowski investigated physical processes in grain-grain collisions, the primary dust destruction mechanism. This study confirmed that dust grains are efficiently destroyed in these collisions, mostly through shattering in collisions with large grains and a more gradual grain erosion by smaller impacts. These processes produce large numbers of small grains, which should be detectable with the Infrared Space Observatory. Further work on destruction of dust grains in radiative shocks is in progress.

Reynolds calculated the synchrotron X-ray emission expected from young SNR shock waves. Electrons accelerated in those shocks should reach energies limited only by the remnant age, electron radiative losses, or absence of suitable upstream scattering turbulence. For the remnants of supernovae less than about 5000 years old, the maximum allowed energies can be above 100 TeV (10^{14} eV), allowing the production of synchrotron X-rays to 10 keV and beyond. The spectral shape is gently curving downward, made up of the sum of many exponentials of different cutoff energies broadened by convolution through the single-electron synchrotron emissivity. The spectra are well approximated by power-laws over a limited bandpass. Reynolds, with undergraduate A. Hornschemeier, has generated families of spectral and morphological predictions for the models, and in particular has fit the X-ray spectrum and image of the remnant of SN 1006, in which X-ray emission from the bright limbs has recently been shown to be nonthermal. Low-level X-ray emission outside the main shock is expected from electrons diffusing ahead of the shock.

Reynolds, in collaboration with D. Moffett (New Mexico Tech), G. Dubner, E. Giacani, and E. Reynoso (Instituto de Astronomia y Fisica del Espacio, Argentina), J. Dickel (Illinois), F. P. Winkler (Middlebury College), and W.M. Goss (NRAO), has begun a second-epoch VLA study at 21 cm of Tycho’s supernova remnant. They plan to compare the new images with observations made in 1983-84 to search for changes in the remnant’s small-scale structure with time, and to better refine the expansion rate and its azimuthal variations. Preliminary data, in comparison with Public Archive ROSAT images of Tycho, show spectacular agreement in the location of the remnant edge in radio and X-rays, with important consequences for theories of electron acceleration and heating.

Reynolds, with graduate student K. Dyer and undergraduate A. Danagoulian, continues work on the radio-bright SNRs 3C 396 and 3C 397, observed with the VLA. Both objects show extensive fine-scale structure. 3C 397 is unpolarized at 20 cm but shows interesting polarized-intensity structure at 6 cm, with a hint of high interior polarization.

Reynolds, with Moffett and D. Wilner (CfA), obtained data from the NRAO 12-m telescope on the SNR 3C 391 in CO. Ambient emission was seen up to the edge of the bright radio-continuum shell, where it disappeared abruptly. The image represents very strong morphological evidence for the association of 3C 391 with molecular gas, as Reynolds and Moffett conjectured earlier, and shows that SNR shock waves moving into mostly neutral gas can still accelerate relativistic particles. Follow-up studies are planned.

Reynolds, with Moffett and N. Kassim (NRL), continued a project to map four bright, compact SNRs (3C 391, 3C 396, 3C 397, and W49 B) with high sensitivity at 90 cm, to compare with images in hand at 20 and 6 cm, to search for spectral-index variations and curvature in the local spectrum of these objects, as predicted by nonlinear theories of shock acceleration. Preliminary images of W49 B, using new high-fidelity imaging software, have attained a factor of 10 better sensitivity than earlier efforts.

Reynolds, with R. Blandford and M. Lyutikov (Caltech) and F. Seward (CfA), observed two radio-bright SNRs with ROSAT: G11.2-0.3 and 3C 397. They showed from spectral studies of G11.2-0.3 that it is almost certainly the remnant of the historical supernova of 386 AD, and that the X-ray image resembles the radio image very closely, again demonstrating the spatial coincidence of processes heating and accelerating electrons. 3C 397 also showed a strong resemblance to the radio image earlier obtained by Reynolds, and its spectrum, poorly fit by simple models, indicates a relatively high temperature and probably non-equilibrium ionization (NEI) conditions. Based on this evidence, Reynolds, with J. Hughes (CfA) and H. Tsunemi (Osaka) obtained an ASCA spectrum of 3C 397 which shows strong evidence for NEI conditions as well as for a very hard spectral component. Analysis of this spectrum is under way.

Reynolds and Seward, with undergraduate T. Coffey, also observed the SNR DA 530 with ROSAT, finding it to be barely visible in X-rays, and possessing an X-ray to radio luminosity ratio lower than that of the relatively faint SN 1006 remnant by a factor of 50, and indicating that DA 530 is quite an old object.

4.3 Planetary Nebulae

Borkowski continues his involvement in observational and theoretical studies of exotic hydrogen-poor planetary nebulae (PNe). Imaging and spectroscopy with the Hubble Space Telescope revealed photoevaporating clumps with tails and high velocity flows arising in the interaction of stellar winds with the clumpy stellar ejecta. These ejecta are very dusty. Future observations with the Infrared Space Observatory will shed light on the nature and the distribution of this carbonaceous dust. Another research area involves X-ray emitting PNe. HST and ASCA observations of these objects revealed mass-loaded flows, stellar-wind blown bubbles, nitrogen-rich stellar ejecta, and stellar jets.

4.4 Stellar Jets

The Spring 1995 Class of PY 228, Stellar Astrophysics, taught by **Blondin**, undertook a group research project investigating the origin of the purported superjet observed by Bally and Devine (ApJ 428, L65). After background research on stellar jets and Herbig-Haro objects, the class developed competing theories to explain the origin of the long train of bowshocks observed in alignment with the young stellar object, HH34*. These theories included a periodicity in the jet outflow with a very long period and short duty cycle, and a low-frequency precession. The students then used a computational hydrodynamics code to study the consequences of their theories, and compared them with the observed properties of the HH34 Superjet. They found that the precession itself could not produce the periodic emission, but the combination of periodic outflow coupled with precession could produce a structure similar to the superjet.

4.5 Binary Stars

In collaboration with M. Richards (Virginia) and undergraduate student M. Malinowski, **Blondin** has used two and three dimensional simulations to study the mass-transfer process in the Algol binary star system. The nature of the mass transfer depends strongly on the role of radiative cooling of the circumstellar gas, which in turn depends on the density of the gas in the tidal stream. For parameters expected in the Algol system, a high-pressure region is formed near the mass-gaining star along the line of centers, where the circumstellar gas orbiting the star (a ‘‘transient’’ disk) runs into the tidal stream. The results of these simulations will be used to interpret Doppler tomography data of Algol-type systems.

Graduate student M. Owen and Blondin have continued to develop a numerical model of high-mass X-ray binaries to study mass transfer and evolution in such systems. This work has included a careful treatment of the boundary conditions at the surface of the primary star such that full Roche lobe overflow can be simulated, the addition of X-ray attenuation in the circumstellar gas to account for the high optical depths encountered in the dense tidal stream and other circumstellar features, the self-consistent generation of X-ray luminosity, and the addition of radiation pressure due to the local X-ray flux. Current work is focussing on a comparison of this 3D numerical model with X-ray observations of LMC X-4, and on the role of the size of the primary relative to the tidal radius in explaining the X-ray flux and other observational properties of high-mass X-ray binaries (HMXBs).

Blondin, with I. Stevens (U. Birmingham, UK) and undergraduate J. Layton, is applying the HMXB model to eccentric binary systems such as GX 301-2. In this highly eccentric system the primary star exceeds its tidal radius for a brief fraction of the orbit near periastron. These simulations are aimed at identifying the temporal behavior of the mass accretion rate due to tidal interactions, as well as the amount of mass and angular momentum lost from the system.

4.6 Shock Waves and Particle Acceleration

One of the longstanding problems of astrophysics concerns particle injection and acceleration at collisionless shocks. **Ellison**, along with M. Baring and F. Jones (NASA/GSFC), has developed a Monte Carlo simulation of diffusive shock acceleration at oblique collisionless shocks. The simulation includes cross-field diffusion and nonlinear shock smoothing, and determines the absolute injection efficiencies of various ion species. The rate at which particles are accelerated is also determined; this depends on the obliquity angle that the upstream magnetic field makes with the shock normal. The greater the obliquity the greater the rate, and in quasi-perpendicular shocks rates can be hundreds of times higher than those seen in parallel shocks. In many circumstances pertaining to evolving shocks (e.g., supernova blast waves and interplanetary traveling shocks) or where acceleration competes with losses (e.g., through synchrotron cooling), high acceleration rates imply high maximum particle energies and obliquity effects may have important astrophysical consequences.

However, the efficiency for injecting thermal particles into the acceleration mechanism also depends strong- ly on obliquity and, in general, more oblique shocks are less capable of injecting thermal particles into the acceleration process. In addition, the degree of turbulence and the resulting cross-field diffusion strongly influence both injection efficiency and acceleration rates. It has been found that turbulence must be quite strong for high Mach-number, highly oblique shocks to inject significant numbers of thermal particles and that only modest gains in acceleration rates can be expected for strong oblique shocks over parallel ones if the only source of seed particles is the thermal background.

In work with K. Ogilvie (NASA/GSFC), spectra produced by this Monte Carlo simulation, of both protons and heavier ions, have been shown to be in good agreement with observations made by the Ulysses spacecraft at interplanetary shocks. The parameters required to fit the observations imply that substantial wave-particle interactions are taking place producing strong collisionless scattering. Future work will involve comparisons between the model predictions and Ulysses observations of pickup ions. Pickup ions, i.e., interstellar neutral atoms which freely enter the heliosphere and are then ionized by either radiation or collisional processes, offer an ideal test of injection physics.

Ellison and graduate student **Bennett** have been using plasma simulations to investigate particle injection and acceleration at shocks. These simulations self-consistently determine the electric and magnetic fields from the motions of individual particles and are able to determine the complex plasma physics occurring in collisionless shocks. Thus far, hybrid simulations (i.e., where protons are treated kinetically as particles, but the electrons are approximated as a massless, charge neutralizing fluid) have been used because they can run long enough to study proton acceleration to relatively high energies. In collaboration with J. Giacalone (Arizona) and D. Burgess and S. Schwartz (Queen Mary College, London), Ellison and Bennett have added particle splitting and pre-existing waves to the standard hybrid simulation, allowing particle energies to be obtained that are high enough to model spacecraft observations at planetary bow shocks and interplanetary traveling shocks.

Bennett has developed a method to stop the shock in the simulation box which allows a true steady-state simulation to be performed and enables the simulation to be run for an arbitrary time with a constant number of simulation particles. Until now, hybrid simulations were intrinsically time-dependent, obscuring any time variability inherent to the shock formation. Using this technique, Bennett and Ellison have investigated the intrinsic variability of quasi-parallel shocks (up to an obliquity of 30°) and shown that particle injection into the Fermi acceleration mechanism is extremely smooth down to time scales on the order of a thermal ion gyroperiod. These limits are considerably tighter than previous work which used much smaller simulation boxes with poorer statistics.

Bennett and Ellison are currently using the steady-state simulation technique to investigate the effects of perturbations on the shock structure and shock reformation time. Results have been obtained for perturbations in density and in magnetic field. In both cases, it is found that, while the perturbations can deform or temporarily disrupt the shock, they have little effect on the acceleration of particles. And, after the perturbation has passed through, the shock quickly returns to its previous state. It is therefore concluded that the Fermi acceleration mechanism is quite robust and not easily disrupted. This work has been performed on the Cray supercomputers of the North Carolina Supercomputing Center.

Ellison, in collaboration with B. Lembege (CNET/ CETP, France) and A. Mangeney (Observatoire de Paris-Meudon, France) is beginning work on 3-D hybrid shock simulations which will be compared directly with the simpler Monte Carlo model mentioned above. Recent work by R. Jokipii and collaborators (U. of Arizona) has shown that if the dimensionality is restricted, as in a one- or two-dimensional simulation, cross-field diffusion is artificially limited. This may have important consequences for particle injection in oblique shocks and 3-D simulations need to be performed to resolve the issue.

In related work, Ellison, along with J.P. Meyer (Service d'Astrophysique, Saclay, France) and L. Drury (Dublin Institute for Advanced Studies, Ireland), is investigating the composition of galactic cosmic rays and changes in source composition occurring during shock acceleration in supernova remnants. The latest observational evidence points toward elements with low volatility being overabundant in cosmic rays compared to solar system abundances. This implies that ISM material which is locked in grains is preferentially accelerated to cosmic ray energies. A shock model of grain acceleration, including nonlinear shock smoothing, is currently being developed and preliminary results suggest that large enhancements of grain material may occur during shock acceleration.

If supernovae produce the bulk of the cosmic rays, as is currently believed, gamma rays will be produced by interactions between the high energy nuclei and ambient material. The same nonlinear effects which produce enhanced grain acceleration will produce non-power-law gamma-ray spectra which may be observable with future space missions. Ellison, along with M. Baring (NASA/GSFC), I. Grenier, and P. Goret (both at Service d'Astrophysique, Saclay, France), is developing shock acceleration models to predict the gamma ray fluxes expected from young SNRs. Improved gamma ray emissivity calculations are being performed using the latest cross-sections determined from reactor experiments.

Knerr, Jokipii, and Ellison have developed a new method for simulating time-dependent, planar, parallel, collisionless shocks. This new dynamical Monte Carlo method requires that all particles scatter elastically and isotropically in their local flow frame, and that a particle's mean free path is proportional to its velocity. Their results clearly show the acceleration of thermal particles to high energies via the first-order Fermi mechanism. The accelerated particle population, via its ''backpressure'' on the incoming plasma, smooths the shock transition creating a distinct shock precursor region and a subshock.

Knerr has also spent time porting a time-independent Monte Carlo code, which follows the orbital motions of individual particles, to a parallel-processing supercomputer (the Cray T3D at the North Carolina Supercomputing Center). This code will be used to study particle acceleration in steady-state collisionless shocks.

5. ACKNOWLEDGMENTS

During this report period, astrophysical research at North Carolina State University has been supported by internal funds from the Physics Department and from the Provost's Office. Extensive support from the North Carolina Supercomputing Center is also gratefully acknowledged. External support was provided by NASA, NSF, and Sigma Xi.

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