

**Ohio University**  
**Department of Physics and Astronomy**  
*Athens, Ohio 45701*

[S0002-7537(93)24141-5]

The following report covers the period November 2000 through October 2001.

## 1. INTRODUCTION

Ohio University was the first institution of higher education in the Old Northwest, and is part of the state university system of Ohio, with a current enrollment of approximately 20,000 students. Ohio's Department of Physics & Astronomy has 24 faculty active in research in areas including nuclear physics, biophysics and nonlinear dynamics, condensed matter and surface physics, and astrophysics. The Department offers a Ph.D. in physics, with a current graduate enrollment of approximately 60 students. Additional information about the Department can be found at the WWW site <http://www.phy.ohiou.edu> .

## 2. PERSONNEL

Astrophysics faculty in the Department include Brian McNamara, Joseph Shields, Thomas Statler, Emeritus Professor James Dilley, and Instructors George Eberts and Tom O'Grady. Additional faculty in the Department engaged in astrophysics-related research include Carl Brune and Daniel Phillips. Ivan King from the University of California at Berkeley held a temporary appointment in April as Rufus Putnam Visiting Professor. The University awarded the Department of Physics and Astronomy a new tenure-track faculty line to expand the Astrophysics Group, and a search for this position is in progress at the time of writing.

During the past year McNamara supervised research by graduate students Laura Birzan and David Rafferty, and undergraduate Russell Ryan. Statler supervised research by graduate student Robert Salow and undergraduates Tim Lester and Daniel Wik. Shields supervised research by graduate students Anca Constantin and Manavi Jadhav. Jadhav completed a masters degree in physics in June, and has since entered the graduate program in geology at Ohio University.

Statler's research on the structure and evolution of elliptical galaxies received new funding from the *Chandra X-ray Observatory* ( *CXO*) and continuing support from an NSF Faculty Early Career Development (CAREER) Award. This funding also allowed the continuation of the Science Teachers Active in Real Science (STARS) program into its fourth year. As part of this program, Kathleen Moore [Botkins High School] spent the summer working with Statler, using a portable 10-inch telescope with CCD and standard filters to image the nucleus and coma of Comet LINEAR (2001 A2). Jessica Lancaster, a student from Lancaster High School, used the same equipment to complete a project with Statler on multicolor imaging of the Ring Nebula (M57). Statler was elected to a 2-year term on the Committee of the AAS Division on Dynamical Astronomy, and served on one of the *HST* Cycle 10 peer review panels.

McNamara received new and continuing funding from NASA, STScI, the Department of Energy, and the *CXO*, including a NASA Long Term Space Astrophysics grant for projects related to X-ray emission in clusters and the optical and radio properties of giant central cluster galaxies. McNamara served on peer and cost review panels for Cycle 3 of the *CXO*, and was appointed to the Telescope Allocation Committee for the National Optical Astronomy Observatories.

Shields received new and continuing funding from STScI and the *CXO* for studies of active galaxies. Shields served as a panelist for the Cycle 3 *Chandra* peer review, and continued as a member of the Telescope Allocation Committee for the National Optical Astronomy Observatories. Shields was named to a three-year term as Scientific Editor for the *Astrophysical Journal*, with duties commencing in October.

## 3. RESEARCH

### 3.1 Normal Galaxies

The reliability of elliptical galaxy intrinsic shape estimates using surface photometry and multi-position-angle stellar kinematics was assessed by Statler with former graduate students H. Lambright and J. Bak. Simulated merger remnants from Weil & Hernquist (1996) were "observed" using software developed by Bak, and then modeled as real systems. The shapes of individual objects are found to be correctly reproduced to within the statistical errors, but with a small systematic bias in the sense of underestimating both the triaxiality and short-to-long axis ratio. Parent shape distributions estimated from samples of independent, randomly oriented objects are also statistically accurate, but on average slightly biased in the same sense. The magnitude of the bias is smaller than 0.1 in either shape parameter, supporting the continued use of these methods on real systems. Recent long-slit spectra for NGC 4472 and NGC 2768 obtained at the Mayall 4m telescope are being reduced by undergraduate student T. Lester, for use with these techniques.

*Chandra*/ACIS observations of the young ellipticals NGC 1700 and NGC 5018 by Statler and McNamara were completed in 2000 and 2001. These galaxies are part of a sample defining an age sequence at the same optical luminosity and in similar environments. The objectives are to obtain accurate X-ray surface brightness profiles, to derive radial profiles of gas density, temperature, and metallicity within the optical radii, and to search for substructure related to inhomogeneous gas flows, tidal debris, and interactions with neighboring systems. The data are currently being reduced; preliminary results for NGC 1700 show the first known case of an elliptical galaxy in which the X-ray isophotes are flatter than the optical isophotes. This system appears to harbor an extended, cooling X-ray disk. The large radial extent of the disk suggests that the gas may have been accreted, rather than having been shed from the galaxy's own stars.

Statler continues a collaboration with D. Terndrup, B. Ryden, and R. Pogge [Ohio State U.] to study the stellar populations and morphologies of dwarf ellipticals in the Virgo cluster. Observations for this project are complete, after three runs on the MDM Hiltner 2.4m in 1998, 1999, and 2000. Much of the data has been reduced by undergraduate students M. Krejny and D. Wik. The 1998 run also yielded a serendipitous discovery of a large shell system in the normal elliptical NGC 2634, for which additional data were obtained in photometric conditions by J. van Gorkom and C. Liu [Columbia U.]. H I maps were obtained in 2000 at the VLA in D array. A stream of H I extends from the nearby spiral NGC 2634A, though no obvious connection exists between the H I and NGC 2634 or its shells, and there is no clear optical evidence of interaction between the two systems. At least 5 shells in NGC 2634 can be seen in the optical images between about 50 and 170 arcsec. The plan is to use the spacing of the shells to constrain the radial mass distribution of NGC 2634 and the age of the shell system, and the kinematics of the H I stream to constrain the orbit of NGC 2634A and discern the evolutionary state of the HG90 group, of which these galaxies are the central members.

### 3.2 Galaxy Nuclei

Salow is continuing work on the double nucleus of M31, as part of his dissertation research under Statler's supervision. He and Statler have shown that models of weakly self-gravitating, finite dispersion eccentric stellar disks can be constructed which have kinematic profiles that closely resemble those seen in M31 (Salow & Statler 2001). These models possess distinctive multi-peaked line-of-sight velocity distributions (LOSVDs) along lines of sight near the central black hole. The distinctive LOSVD features should be observable in M31 at the resolution of STIS, and can be used to identify the eccentric nuclear disk in M31 and determine the mass of the central black hole.

Salow and Statler have recently developed an N-body code to examine the stability of particle realizations of disks constructed via the scheme described in Salow & Statler (2001). The code, which uses a time-symmetric Hermite integrator (Kokubo, Yoshinaga, & Makino 1998), is well suited for the study of stellar systems with many eccentric orbits that pass close to a central black hole.

A remarkably simple family of analytic models for razor-thin (two dimensional) eccentric Keplerian fluid disks was constructed and studied by Statler. In these models, flow along streamlines of constant eccentricity creates a configuration in which there is no compression of the fluid, and therefore no dissipation due to bulk viscosity. The pressure gradient drives a precession whose frequency is the same at all radii. These disks could therefore be long-lived at significant eccentricities if the shear viscosity is negligible. Low-eccentricity models can be seen as axisymmetric disks perturbed by a traveling acoustic wave similar to an ocean wave. The expected emission line profiles from the eccentric disks are strongly asymmetric in general, and, in extreme cases, prone to misinterpretation as single narrow lines with significant velocity offsets.

The nucleus of the "standard elliptical" NGC 3379 is the subject of work by K. Gebhardt [U. Texas] and Statler using the *Hubble Space Telescope* (*HST*) with WFPC2 and STIS to resolve the inner arcsecond of the stellar and gas distribution and kinematic fields. Imaging was carried out in Cycle 9; spectroscopy has been delayed due to STIS hardware problems and is scheduled for the end of 2001. This work is a follow-on to Statler's earlier dynamical modeling of ground-based kinematic data, which showed that the main body of NGC 3379 is most probably axisymmetric and oblate in the inner parts, with an outward triaxiality gradient. Short-axis inclinations  $i$  between  $30^\circ$  and  $50^\circ$  are preferred for nearly axisymmetric models; but triaxial models in high inclination are also allowed, which can affect central black hole mass estimates. The models rule out the possibility that the nuclear dust ring at  $R \approx 1''.5$  is in a stable equilibrium in one of the galaxy's principal planes. The ring is thus a decoupled nuclear component not linked to the main body of the galaxy.

Shields is continuing his collaboration with H.-W. Rix [MPIA-Heidelberg], L. Ho [OCIW], A. Filippenko [UC-Berkeley], M. Sarzi [Padova], A. Barth and W. Sargent [Caltech], and G. Rudnick and D. McIntosh [Steward Obs.] in a study of the emission properties and small-scale kinematics for a sample of nearby, weakly active nuclei using *HST* and STIS. While the majority of the observed sources show spatially resolved nebular emission, only  $\approx 25\%$  of the sample was found to exhibit regular kinematics consistent with motions dominated by gravity. Further scrutiny of these sources has demonstrated that the regularity of dust absorption in unsharp-masked images of the nucleus can be used as a predictor of well-behaved rotational kinematics. The sources with gravity-dominated rotation curves were previously analyzed to obtain mass estimates for central black holes; the full dataset has recently been employed to place upper limits on black hole masses, based on the velocity width of the central, spatially unresolved, line emission. The results are in general accord with other work demonstrating correlations between black hole mass and the bulge stellar velocity dispersion or mass.

Shields is collaborating with a team led by T. Böker [STScI] in a study of nuclei in late-type galaxies. This work includes an imaging snapshot survey of 77 objects with *HST*, which has revealed a distinct, compact, and dominant source at or very close to the centers of most of these galaxies. The central sources are spatially resolved in the majority of cases, and evidently represent compact star clusters. Analysis is in progress to quantify the properties of these clusters and the extent to which they resemble globular and compact star clusters in other environments. In a follow-on project, *HST* spectra are being acquired in snapshot mode of central sources identified from the imaging program. These data will make it possible to constrain the age and star-formation history of the nuclear clusters.

B. M. Sabra [U. Florida], Shields, Ho, Barth, and Filippenko continued their study of low-ionization nuclear emission-line regions (LINERs) observed spectroscopically with *HST*. The data reveal that UV resonance line absorption is a common attribute of these sources. Unlike the absorbers

seen in Seyfert galaxies and QSOs, however, the lines found in LINERs tend to have low ionization and only small velocity differences from the host galaxy. It is therefore questionable whether the absorbers are actually associated in a fundamental way with the nucleus, rather than simply representing interstellar material in the host galaxy that happens to fall along our line of sight. These results may have important bearing on understanding the luminosity dependence of intrinsic absorbers associated with AGNs.

Shields, working with M. Eracleous and G. Chartas [Penn State] and E. Moran [UC-Berkeley], completed a study of LINERs with *Chandra*. The improvement in spatial resolution over previous X-ray telescopes makes it possible to distinguish distinct components in the nuclei and their environs, which have previously been treated as single unresolved sources. Three galaxies were analyzed, and show heterogeneous properties: NGC 404 shows only weak X-ray emission; NGC 4579 shows a central dominant source that is evidently a classical AGN; and NGC 4736 shows a collection of discrete X-ray sources apparently tracing a recent starburst, with no clear indication of a distinctly nuclear object. These findings reinforce earlier indications that LINERs form a heterogeneous class in terms of their underlying energy sources and excitation mechanisms.

R. Pogge [Ohio State U.], Shields, and P. Martini [OCIW] were awarded *HST* Cycle 10 time to observe a sample of nearby Seyfert 2 nuclei with STIS. This project will take advantage of *HST*'s spatial resolution to study the emission-line and continuum properties of these systems on small scales. The results will have bearing on the structure of Seyfert 2 nuclei and the extent to which the observational properties of these sources are influenced by aperture effects.

Constantin and Shields, in collaboration with F. Hamann [U. Florida], C. Foltz [MMT Obs.], and F. Chaffee [Keck Obs.], have recently completed a detailed analysis of the rest-frame UV emission-line properties of QSOs at  $z > 4$ . The study employs a sample of 44 objects for which high signal-to-noise spectra were obtained over multiple observing runs at the MMT and Keck Observatories. Comparisons of composite spectra show that the  $z > 4$  sources strongly resemble their lower redshift counterparts. Subtle differences are present, however, in the profiles and strength of some emission lines. In particular, the high redshift data bolster indications of supersolar metallicities in the broad-line region plasma, which support scenarios that assume substantial star formation at epochs preceding or concurrent with the QSO phenomena. The degree to which these findings may be influenced by selection effects is a possible concern. Quantitative comparisons with other existing surveys of high redshift QSOs, including those discovered by the Sloan Digital Sky Survey, suggest that the sample studied here is not strongly biased, or in any case, subject to selection effects that are not significantly different from the other available samples.

As part of a team led by J. Bechtold [U. Arizona], Shields is continuing a study of the X-ray properties of QSOs at  $z > 4$  using *Chandra*. A total of 14 objects will have been observed by the conclusion of Cycle 2. The results indicate that these sources show UV/X-ray spectral energy distributions (SEDs) that are similar to QSOs at lower redshift.

Analysis in progress will examine the SED behavior in these objects as a function of the black hole mass estimated from emission-line properties.

### 3.3 Galaxy Clusters

McNamara and colleagues were awarded several *Chandra* Cycle 3 programs designed to probe the relationships between cooling flows, radio sources, and star formation. One of the areas of investigation concerns the origin of large-scale cavities in the thermal cluster X-ray emission. The cavities, seen in many clusters observed with high resolution *Chandra* imaging, are usually filled with radio synchrotron emission associated with the lobes of powerful radio galaxies. The cavities appear to be in pressure balance with the hot intracluster medium (ICM), and are supported by cosmic rays, magnetic fields, and possibly a very hot, dilute gas. McNamara, colleagues, and students are investigating the systematic properties of cavities over a large sample of clusters with the goal of understanding the life cycles and composition of galactic radio sources, and the transfer of energy and momentum from the radio sources to the keV gas. McNamara has joined scientists at Los Alamos National Laboratory, including H. Li and S. Colgate, and several university investigators in a new collaboration to investigate the origin and dynamical significance of magnetic fields in clusters and their influence on galaxy formation. One of the principal goals is to create realistic magnetohydrodynamic models of the radio-filled cavities observed in clusters with *Chandra*.

In related research, McNamara and his collaborators have discovered “ghost” cavities in the Abell 2597 cluster. Unlike the radio-bright cavities seen in the Hydra A cluster, for example, ghost cavities inhabit the regions beyond the bright central radio source. McNamara *et al.* interpret the ghost cavities as the product of an earlier radio event. The existence of ghost cavities implies a radio cycling timescale of roughly 100 Myr, and they may provide the means for magnetizing the intracluster media of cooling flow clusters.

McNamara, S. Murray [SAO], M. Wise [MIT], C. Sarazin [U. Virginia], and others have continued their studies of X-ray emission in several clusters, including Abell 1068. Abell 1068 is luminous in X-rays and has been reported to contain a  $400 M_{\odot} \text{ yr}^{-1}$  cooling flow. The central galaxy in the Abell 1068 cluster is remarkable in several respects. It is experiencing a vigorous episode of star formation at a rate of  $80 M_{\odot} \text{ yr}^{-1}$ . In addition, it is a luminous infrared source that would nearly qualify as an “ultraluminous infrared galaxy.” McNamara, Murray, and Wise are analyzing a new *Chandra* image of Abell 1068 that has revealed a remarkable degree of structure in the center of the cluster. The team is investigating whether the X-ray cooling rate and star formation rates match, as would be expected if star formation is fueled by the cooling flow.

A collaboration comprised of P. Nulsen [U. Wollongong], L. David [SAO], McNamara, C. Jones [SAO], W. Forman [SAO], and Wise has completed a detailed study of the interaction of the radio source Hydra A with the associated ICM. *Chandra* observations of this source do not exclude weak shocks as an agent in producing the cavities in the X-ray emission. However, the bright, X-ray rims cannot be

the result of shock-induced cooling or magnetic fields in shocks, but instead are probably composed of entrained, cool material pulled upward by the rising cavities. The radio source in this object may be capable of significantly reducing or quenching the cooling flow.

E. Blanton [U. Virginia], Sarazin, Wise, and McNamara have analyzed *Chandra* observations of the Abell 2052 cluster. The data reveal holes surrounded by bright shells in the X-ray emission coincident with the radio lobes. As is seen in other clusters, the data are consistent with the radio source displacing and compressing the X-ray gas. The compression of the X-ray shells appears to have been gentle with slightly transonic expansion speeds. The pressure in the X-ray gas is approximately an order of magnitude higher than the minimum pressure derived for the radio source, suggesting that an additional source of pressure is needed to support the radio plasma in this object.

McNamara continued his work on the 160 Square Degree X-ray Cluster Survey in collaboration with the CfA group, headed by A. Vikhlinin, and the Hawaii group (P. Henry, I. Gioia, and C. Mullis). Over the past year this team has obtained results on the optical richness properties of the most distant, X-ray-selected clusters. They found that most clusters detected beyond  $z=0.5$  are Abell richness class 1 and 2, and that the distribution of richnesses is similar to that of nearby clusters identified using similar X-ray criteria. The team has completed a follow-up redshift survey, and is working on constructing the cluster luminosity function. The collaboration has also analyzed observations of strong gravitational lensing in conjunction with *Chandra* X-ray imaging of the  $z=0.5$  cluster, RXJ0030+2618, discovered in the 160 square degree survey. The lensing mass within 120 kpc of the cluster center was found to be twice as large as the X-ray mass, similar to that found in other lensed clusters. RXJ0030+2618 is among the lowest luminosity clusters yet discovered with a strong lensing signal.

### 3.4 Nuclear Astrophysics

Brune has pursued a better understanding of the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  reaction at low energies. The rate of this reaction determines the  $^{12}\text{C}/^{16}\text{O}$  ratio produced by helium burning in stars, and consequently has very significant effects on the subsequent structure and nucleosynthesis, as well as the final outcome of the evolution. Calculation of the reaction rate in helium-burning conditions requires that the cross section be known for energies of  $\sim 300$  keV; unfortunately, at this energy the cross section is too small to be measured with presently available accelerator technology. Instead, the  $\alpha$  transfer reactions  $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$  and  $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$  have been utilized to determine the spectroscopic properties of the  $^{16}\text{O}$  state just below the  $^{12}\text{C} + \alpha$  threshold. These data have been found to place important constraints on the cross section at astrophysically-required energies. Another study focused on the interplay between electric dipole ( $E1$ ) and electric quadrupole ( $E2$ ) contributions to the  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$  cross section. An understanding of the angle- and energy-dependent interference effects between the  $E1$  and  $E2$  am-

plitudes is found to be important for interpreting existing experimental data and also for extrapolating them to lower energies.

Brune is also involved in a program to measure reactions relevant to nucleosynthesis in stellar explosions with radioactive beams at Oak Ridge National Laboratory (ORNL). This collaboration, which includes scientists from ORNL, Yale, UNC-Chapel Hill, and Tennessee Tech, has studied several important reactions involving  $^{17}\text{F}$  and  $^{18}\text{F}$ . Measurements of  $^1\text{H}(^{17}\text{F}, ^{17}\text{F})$  have located a  $3^+$  state which largely dominates the  $^{17}\text{F}(p, \gamma)$  reaction rate. The  $^1\text{H}(^{18}\text{F}, ^{18}\text{F})$   $^1\text{H}(^{18}\text{F}, \alpha)$  reactions have also been measured, with the most significant feature found being a strong resonance at  $E_{c.m.} = 665$  keV. In the future it is hoped that sufficient  $^{17}\text{F}$  beam intensity can be developed so that the  $^{17}\text{F}(p, \gamma)$  reaction can be measured directly. These proton-induced reactions on  $^{17,18}\text{F}$  are critical for estimating the quantity of  $^{18}\text{F}$  produced by novae;  $\beta^+$  decay of the latter isotope may produce an observable flux of  $\gamma$  rays with energies up to 511 keV. These reactions also have important effects on the yields of heavier nuclei produced in novae and X-ray bursts.

Phillips has collaborated with C. Hanhart [FZ-Jülich], S. Reddy [Los Alamos], J. A. Pons [INSN-Rome], and M. J. Savage [U. Washington] in studies related to the early evolution and cooling of neutron stars. The evolution of the newly-formed star is characterized by a rapid early cooling phase followed by a significantly slower, late-time cooling phase. During both of these phases neutrinos are an important source of energy loss. Reactions involving nucleons are significant for influencing the propagation, production, and thermalization of neutrinos in the outer regions of the star during the first several seconds of the supernova's evolution. At later times, the neutron star enters a period of slower thermal evolution, during which the emitted neutrinos free stream. The time scale for this long-term cooling depends crucially on the neutrino emissivity. At these late times, the charged-current bremsstrahlung process (also called the modified Urca reaction) is expected to be the main source of energy loss in the neutron-star interior. Observational constraints on this portion of the neutron star's evolution will improve as X-ray observatories such as *Chandra* and *XMM* provide information on the surface temperatures of these stars.

Phillips and collaborators are working to improve models of both the early- and late-time cooling of the neutron star by studying the reactions that control the cooling dynamics. This effort has demonstrated that an approach reminiscent of that used in soft-photon calculations allows one to relate the rate of production of soft-neutrino radiation in nucleon-nucleon ( $NN$ ) scattering to the on-shell  $NN$  scattering amplitude, and thus to experimental data from the  $NN$  system. The resulting neutrino emissivities from the two-nucleon reaction are a factor of four to five lower than those previously employed in neutron-star and supernova simulations. Phillips and collaborators are working with supernova and neutron-star modelers to assess the effect of these results on neutron-star cooling scenarios.

Phillips and co-workers have also been working to set bounds on the existence of large, compact, "gravity-only"

dimensions (GODs). One of the strongest constraints on the existence of GODs comes from SN1987a. If the rate of energy loss into these putative extra dimensions is too high, then the neutrino pulse from the supernova would differ from that actually seen. The dominant mechanism for the production of Kaluza-Klein gravitons and dilatons in the supernova is again radiation from the  $NN$  system—gravitational radiation in this case. Phillips *et al.* have computed the rates for these processes in a model-independent way using low-energy theorems. A re-evaluation of bounds on toroidally-compactified “gravity-only” dimensions indicates that consistency with the observed SN1987a neutrino signal requires that for two such dimensions their radius must be less than 1 micron. A detailed study of the supernova neutrino signal in conjunction with a likelihood analysis has also been used by the team to set one of the more stringent bounds on the size of GODs for the  $n=2$  case. Refinements to calculations of radiation from the  $NN$  system, other improvements to cooling dynamics, and bounds on other exotic particles, will be pursued in future work.

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Joseph Shields