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"Emission Processes and Dynamics of Hot Gases in Astrophysics"

University of Virginia

Roger A. Chevalier and Craig L. Sarazin,
Co-Principal Investigators

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Personnel

Roger Chevalier and Craig Sarazin (both Professors of Astronomy at the University of Virginia) were the Principal Investigators. Co-Investigators were Steven Balbus (Associate Professor), Robert O'Connell (Professor), and Joel Bregman (Scientist at NRAO in Charlottesville). At a part of the development of the Virginia Institute for Theoretical Astronomy (VITA), John Hawley was hired as an Assistant Professor. Post-doctoral fellows who were fully supported by the NASA Theory Program Grant included Peter Becker (Ph.D. University of Colorado), Kamizierz J. Borkowski (Ph.D. University of Colorado), Robert Emmering (Ph.D. University of Virginia), Alexander Kashlinsky (Ph.D. Cambridge University), Stephen Murray (Ph.D. University of California, Santa Cruz), and Noam Soker (Ph.D. Technion, Israel). In addition, Eric Myra (Ph.D. University of Pennsylvania, post-doc at Stony Brook) was hired jointly by VITA and the Commonwealth Center for Nuclear and Particle Physics at the University of Virginia.

Graduate Students

Graduate students who were supported in part by the grant included Geary Albright, Bill Dalton, Robert Emmering, Prudence Foster, Chris Graney, John Houck, Eric Lufkin, John Miller, Phil Plait, and Michael Wise. Foster, Houck, and Wise completed their Masters Degree last year, and Emmering completed his Ph.D.

Undergraduate Students

Greg Ashe and Jay Boisseau, undergraduate astrophysics majors, did his senior theses on research supported by this grant. In both cases, the research lead to published papers. Ashe was supported during part of the summer following his senior year; during this time, he wrote up the work for publication. Both were also supported by the NRAO REU program.

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Research Results

Supernovae and Supernova Remnants

K. Borkowski (post doc on the grant), J. Blondin (post doc), and Sarazin developed a detailed model for Kepler's supernova remnant (SNR). Observations of this SNR have revealed a strong interaction with the surrounding circumstellar medium, which was studied through both analytical and numerical (with a 2-D hydro code) calculations.

Borkowski and M. Shull (Univ. of Colorado) continue to investigate effects of electron thermal conduction on the structure of radiative interstellar shock waves. Their primary goal is to explain the observed line emission from metal-rich ejecta in supernova remnants, incorporating up-to-date atomic data.

Chevalier and R. Emmering (a post-doc on the NASA grant) continued their investigation of light echoes around SN1987A. Analyzing infrared and scattered circumstellar light echoes, they used early observations to set limits on the mass of circumstellar dust. Early in 1989, a light echo was observed that was sufficiently close to the supernova to suggest a circumstellar (i.e. presupernova mass loss) origin. Chevalier and Emmering found that the echo properties were consistent with the shell created by the deceleration of the red supergiant wind by the surrounding pressure if that pressure is low. More recent observations suggest a more complicated morphology and it is plausible that winds from nearby early type stars play a role. In particular, the wind from star 2 may have swept out the slow wind from the supernova progenitor in our direction.

Chevalier and C. Fransson (Stockholm Observatory) completed work on the emission from heavy element gas ejected in the supernova explosion of massive stars. They assumed that a radioactive energy source is present and calculated the detailed heating and ionization of the gas. At times later than 200 days, the emission is dominated by neutral and singly ionized lines, the strongest due to [OI], [CaII], MgI], [CI], and [SiI]. The relative and absolute line strengths depend on both the column densities of the different abundance zones and the relative abundances within each zone. Reliable modeling requires a knowledge of the density structure and the degree of element mixing; emission line profiles are useful for determining these. Data on the late emission from Type Ib supernovae suggests that these are the explosions of massive star cores and are not exploding white dwarfs.

Chevalier investigated the evolution of supernova remnants in the very high pressure environment of a starburst galaxy.

Chevalier modeled the recently observed increase in radio flux from SN 1987A as the result of the interaction of the supernova shock wave with the termination shock of the wind from the blue supergiant progenitor star.

Chevalier, Blondin, and Emmering completed the first part of a study of hydrodynamic instabilities in supernova remnants.

Chevalier and E. Liang (Lawrence Livermore Natl. Lab.) examined the interaction of a massive star supernova with a circumstellar shell resulting from previous mass loss. Self-similar solutions can describe several aspects of the flow. The supernova remnant Cas A is probably a good example of compact shell interactions. The model predicts that the bright X-ray and radio ring is shocked dense wind gas, and hot, shocked supernova gas is inside of the ring. Compact radio sources observed in NGC 4449 and in the starburst nuclei of M82 and NGC 253 may also be compact shell interaction. The model predicts slow expansion of the radio sources and the appearance of new sources with diameters comparable to those of the present sources. This interpretation requires that the starburst nuclei have a large population of massive star supernova progenitors in a blue evolutionary phase. The model can also be applied to the interaction of SN1987A with its circumstellar shell, expected to occur within decades.

Chevalier and N. Soker (a post-doc on the grant) calculated models for the expansion of a supernova envelope like that thought to be present in SN1987A. They showed analytically that the expanding envelope can be divided into an inner region with a flat density profile and an outer steep power law density profile. For SN1987A, the bend in the profile occurs at a velocity of about 4000 km s^{-1}. Polarization and imaging observations show that the envelope expansion of SN1987A is asymmetric, so Chevalier and Soker modeled on asymmetric initial density distribution or energy deposition. The analytic and numerical calculations show that the final degree of asymmetry is comparable in magnitude to the initial asymmetry. The models also show that the sense of density asymmetry changes across the bend in the density profile. This accounts for the different polarization angles observed in the Hα and Ca II lines by Cropper *et al.* in June 1987. The cause for the asymmetry is uncertain. If the progenitor envelope was rotationally flattened, angular momentum transfer from a binary companion during the stellar evolution is probably necessary. An asymmetric initial explosion is another possibility.

Emmering and Chevalier used the observed light curve and temperature evolution, as well as the theoretically predicted initial ultraviolet burst of SN 1987A to construct models for the infrared (IR) echo and scattered light echo arising from circumstellar dust formed in the wind from the supernova progenitor's red supergiant phase. The echo models were constructed by including the detailed emission and scattering of dust grains, and a spectrum of grain sizes were considered. The comparison of the predictions of the IR echo models with the available IR observations led to the conclusion that an IR echo has probably not been observed as of late 1987 and it was possible to set limits on the amount of circumstellar dust. The methods which were developed to study the effects of circumstellar dust around SN 1987A should applicable to observations of other supernovae.

Emmering and Chevalier also investigated the intrinsic luminosity and initial period of pulsars by using Monte Carlo techniques to generate a Galactic sample of pulsars having particular distributions of initial periods, magnetic dipole moments, and positions. By choosing a relationship between the radio luminosity, the period, and the period derivative, it was determined which pulsars of the generated sample could be detected in one of the major pulsar surveys. The properties of the detectable pulsars were compared with the properties of the observed pulsars, and the initial distributions and luminosity relation of the model were adjusted until a satisfactory agreement was obtained. A crucial point is that the observed relation between luminosity and period is affected by selection affects and does not apply to the actual pulsar population. It was found that the best fits were obtained with models in which the pulsars are injected with relatively long periods, about 0.5 sec.

Observations of the supernova 1987A show the presence of asymmetry in the expanding envelope. Hawley and G. Lindahl (graduate student) investigated supernova models that have asymmetric initial density distributions or asymmetric explosions through simulations of nonspherical explosions and point explosions in rotationally flattened envelopes.

J. Houck (a graduate student on the grant) and Chevalier continued work on the hydrodynamics of optically thick, spherically symmetric neutron star accretion in supernovae. They obtained detailed solutions for the steady state accretion flow including Newtonian gravity, a detailed neutrino cooling function and pressure contributions from radiation, electron-positron pairs and baryons. Radiation pressure dominates in most of the post shock region, although pairs become important once the temperature rises above $T \approx 5 \times 10^9$ K. The post shock flow is nearly adiabatic except for a thin zone near the neutron star surface where neutrino cooling is important. They also carried out a linear stability analysis of the accretion flow. Unfortunately, difficulties in solving the resulting system of stiff differential equations severely limited the range of accretion rates for which solutions could be obtained. The solutions that were obtained show that the flow is stable for accretion rates typical of very early times ($\dot{M} \sim 10^6 M_\odot$/yr) and that the flow becomes less stable as the accretion rate decreases. Hydrodynamic modeling was inconclusive due to numerical difficulties.

M. Wise (a graduate student on the grant) and Sarazin calculated the effect of charge transfer reactions on the X-ray line emission of supernova remnants. Recent laboratory plasma physics experiments have shown that charge transfer rates between neutral hydrogen and very highly charged ions are extremely rapid. The charge transfer reactions $H + X^{Z+} \rightarrow H^+ + X^{(Z-1)+}$ occur primarily to levels with $n \approx Z/2$, for which the reactions are nearly resonant. These reactions are important in fusion devices, because the gas may be cool enough near the walls to allow a significant amount of neutral hydrogen. In addition, many fusion devices utilize heating by neutral beams, which results in neutrals being injected directly into the hot plasma. In calculating the X-ray emission from supernova remnants, it is conventional to include only ionization, recombination, and excitation processes associated with collisions between ions and electrons. If a small proportion of the hydrogen behind the shock remains neutral, then charge transfer reactions might affect the ionization state and X-ray line emission of the gas. The presence of neutral hydrogen in the shock requires that the hydrogen entering the shock not be fully ionized. For shocks associated with Type II supernovae or O-star stellar winds, it is likely that the surrounding gas is photo-ionized by the present or pre-supernova early-type stars. However, for Type I supernova or Type II supernova in dense regions, the surrounding gas may well be neutral. Evidence that this is indeed the case comes directly from the observation of broad and narrow Balmer line filaments in a number of supernova remnants, which are produced by charge transfer between rapidly moving protons behind the shock and neutral hydrogen atoms entering the shock. Wise and Sarazin find that charge exchange can affect the X-ray spectra of supernova remnants under some circumstances, but that the effects are not generally very significant.

Interstellar Medium

Balbus and Borkowski concluded a study of the time-dependent non-equilibrium ionization structure and evolution of radiative magnetized plane-parallel thermal conduction fronts in the interstellar medium. The planar cloud geometry is both more simple and probably more realistic than the commonly used isolated sphere idealization. Since planar fronts present less evaporating surface area per unit mass of cool gas compared than do spherical clouds, the predicted densities of such intermediate temperature diagnostic ion species as O VI are below other models, and in better agreement with observations. Furthermore, the time dependence of these fronts is characterized by a rather lengthy period in which important ion column densities (*e.g.*, N V, O VI) evolve very slowly, although this depends somewhat on the magnetic field structure. These fronts are a significant source of UV emission in galactic haloes.

Balbus and B. Dalton (graduate student on the grant) have developed an analytic model for the evaporation of a cold cloud in a hot gas in which the thermal conductivity varies smoothly from a classical diffusive form to a nondissipative, flux-limited form. This model will be of considerable interest because the mathematical form of the flux-limiter used is quite standard in numerical work, but to date no benchmark analytic problem has been available for code testing.

Balbus and Hawley have found that astrophysical accretion disks are generally unstable to axisymmetric disturbances in the presence of a *weak* (subthermal) magnetic fields. The identification of this instability may solve the long standing puzzle over the nature of the physical origin of the turbulent viscosity invoked as a transport mechanism in disks, as well as offer a remarkably simple way to efficiently amplify magnetic fields in rotationally supported systems.

Borkowski, Balbus, and C. Fristrom (post-doc on the grant) studied the evolution of plane-parallel magnetized thermal conduction fronts in the interstellar medium (ISM). Separating the coronal ($\sim 10^6$ K) ISM phase and interstellar clouds, these fronts have been thought to be the site of the intermediate-temperature regions whose presence was inferred from O VI absorption line studies. The authors followed the front evolution numerically, starting from the initial discontinuous temperature distribution between the hot and cold medium, and ending in the final cooling stage of the hot medium. Initially, electron thermal conduction transports energy from the hot to the cold medium, evaporating and heating the cold gas to temperatures slightly over half of the initial hot medium temperature. The front broadens continuously until radiative losses balance conductive heating in the evaporated gas. Subsequently, the evaporated gas cools down and a condensing front propagates into the hot medium. For the typical ISM pressure of $4 \times 10^3\,\mathrm{K\,cm^{-3}}$ and the hot medium temperature of 10^6 K, the transition from evaporation to condensation in a nonmagnetized front occurs when the front thickness is 15 pc. This thickness is by a factor of 5 smaller than previously estimated. The O VI column densities in both evaporative and condensation stages agree with observations if the initial hot medium temperature T_h exceeds 7.5×10^5 K. Condensing conduction fronts give better agreement with observed O VI line profiles because of lower gas temperatures. Collisionally excited C and O lines in both evaporative and condensing fronts, as well as He II 304 Å line in the evaporative front, could dominate the diffuse UV and EUV line emission. A fraction of the observed soft X-ray background may also be produced in a conduction interface. An ordered magnetic field reduces conductive energy transport, but the reduction is substantial only for large inclinations of magnetic field lines in the hot gas to the front normal.

Borkowski, Sarazin, and Soker considered the interaction of a moving planetary nebula (PN) with the interstellar medium. The PN shell is compressed first in the direction of the stellar motion. This produces a dipole asymmetry in the surface brightness of the nebula, typically at a nebular density of $\sim 40\ \mathrm{cm^{-3}}$ if the nebula is located in the galactic plane. In the later stages of the interaction, this part of the shell is significantly decelerated with respect to the central star, and the PN becomes strongly asymmetric in shape. This distortion and the subsequent stripping of the nebular gas away from the central star typically occurs at a low nebular density of $\sim 6\ \mathrm{cm^{-3}}$. Borkowski, Sarazin, and Soker examined the morphology of PNs with central stars whose proper motions exceed 0.015 arcsec $\mathrm{yr^{-1}}$, and found that many of the extended nebulae are interacting with the interstellar medium (ISM). Their sample doubles the number of known PNs interacting with the ISM. They also examined the morphology of nearby PNs, and found a number of strongly asymmetric nebulae. The expectation is that the central stars in these PNs should have large proper motions, and the authors predicted the directions from the observed asymmetries. They suggested the use of interacting PNs to determine the filling factor of the warm neutral and ionized components of the ISM.

Bregman and Houck completed their investigation of the behavior of low temperature galactic fountains. Observations show that neutral gas is present in the halo of the galaxy with a characteristic height of 1 kpc, $N_H \approx 10^{19} - 10^{20}$ cm^{-2}, and -100 km/s $< v <$ 100 km/s. To examine whether these observations can be reproduced by the galactic fountain model, analytic as well as one and two dimensional hydrodynamic calculations were performed. The temperature and density at the base of the halo are the important free parameters. Fluid flow in the halo was calculated in a Cartesian frame with a constant gravitational force and optically thin radiative losses. When the cooling time t_{cool} is less than the sound crossing time t_s in the halo gas, a transonic fountain occurs in which cool clouds are produced in the upward flow. If $t_s < t_{cool} < 10t_s$, a steady subsonic fountain occurs, also with a well-defined cloud formation layer. In these cases, the density at the base of the flow determines the velocity and mass flux, while the choice of temperatures determines the height of the cloud formation layer. For halo pressures appropriate for the solar circle, transonic flow occurs for $T < 3 \times 10^5$ K and $n < 1.5 \times 10^{-3}$ cm^{-3}. When $t_{cool} > 10t_s$ (which occurs when $T > 10^6$ K and $n < 5 \times 10^{-4}$ cm^{-3}), convective or Rayleigh-Taylor instabilities disrupt the steady flow, broadening and complicating the region of cloud formation. The model that best reproduces the observations is near the transonic regime and has a temperature and density at the base of the fountain of $T = 3 \times 10^5$ K and $n = 1 \times 10^{-3}$ cm^{-3}. The cooling time for the hot gas is $t_{cool} = 3.3 \times 10^7$ yr and the time for newly formed clouds to return to the disk is 4.7×10^7 yr, neglecting drag forces. If extended uniformly over the galaxy using a radius of 10 kpc, the mass flux rate onto one side of the disk is 0.2 $M_\odot$/yr and the energy radiated is 2.9×10^{39} ergs/s, mostly in the extreme ultraviolet region.

P. Plait (a graduate student on the grant) and Soker studied the density and mass profile of the planetary nebula NGC 6826. They discussed the possible formation of the dense shell at the edge of the nebula as a result of interaction with the ISM. The formation of the spherical outer halo together with an elliptical inner region can be explained by a low mass companion to the progenitor of NGC 6826 that was evaporated or collided with the central star.

Sarazin and C. Graney (a graduate student on the grant) have calculated the emission from gas at temperatures of $T \sim 10^6$ K due to optical coronal lines that result from fine structure transitions within the ground states of highly ionized atoms. These lines include the [Fe X] λ6374 line, the [Fe XIV] λ5303 line, and many other lines from stages of ionization of S, Ca, Fe, and Ni. The calculations are valid in the limit of very low density, and apply to the diffuse gas found in supernova remnants, the interstellar medium in galaxies, and intergalactic gas. The calculations are done for two physical situations. First, the optical coronal line emission is calculated for a gas in ionization equilibrium for temperatures between 10^5 and 10^7 K. The results were given as a function of the density and of the pressure of the gas. Second, the emission of a gas cooling under its own radiation is calculated. The emission is calculated for gas cooling at either constant pressure (isobarically) or constant density (isochorically). The effects of nonequilibrium ionization are included, but Graney and Sarazin find these to be insignificant. They also find that the amount of optical coronal emission produced by a given amount of cooling gas is largely unaffected by changes in element abundances (providing the proportions of heavy elements remain the same).

Soker studied the formation mechanisms for the two optical bright knots in planetary nebulae, which are called "ansae". Soker used a two-dimensional hydrodynamic code to study the shaping of young asymmetrical planetary nebulae. He suggested that the shape of a young asymmetrical planetary nebulae may be influenced by a close binary-star system located at its center. This binary system is a relic of the common envelope phase, presumably through which the asymmetrical planetary nebula evolved. He assumed that for a short period of time, shortly after the cease of the slow wind and long before the fast wind becomes effective, the binary system ejects a small amount of mass, mainly in the equatorial plane. He found that at late times the high density region has a "horseshoe" shape, as viewed in the symmetry plane. There is an instability in the maximum density region.

In order to provide a theoretical framework for observations of interacting PNs, Soker, Borkowski, and Sarazin calculated hydrodynamical models of PNs interacting with the ISM. In most cases, their results are in fair agreement with those obtained with the help of a thin-shell approximation, and agree with observational data. This simple picture breaks down for a high-velocity PNe in a low density environment, where the shocked ISM cools down slowly. In such a case, a Rayleigh-Taylor instability develops, leading to the shell fragmentation. Soker, Borkowski, and Sarazin discuss in this context a recently discoved PN in the globular cluster M 22, which is being stripped away from the cluster by the ram pressure of the ISM. Similar considerations are of importance in elliptical galaxies where PNs are stripped away from their central stars by the hot ISM, whose presence is inferred from X-ray observations.

Soker and M. Livio (Technion, Haifa) used two dimensional hydrodynamics to investigate the problem of shaping of planetary nebulae by the interacting winds model. They obtained the shock structure and demonstrated that interacting winds are capable of producing morphologies similar to the ones observed in planetary nebulae, provided that a density contrast exists between the equatorial and polar directions. They discussed mechanisms that can produce the required density contrast and showed that binary central stars provide the most natural mechanism, especially via common envelope evolution. It is not yet entirely clear whether stellar rotation is sufficient to generate the required contrast in the cases of single central stars. They finally pointed out that interacting winds may play an important role in SN1987A.

Hot Gas in Elliptical Galaxies

Bregman and J. Boisseau (an undergraduate astrophysics major at Virginia) investigated a particle acceleration model with application to the AGN environment. They considered a time dependent model in which plasma enters a shock region and undergoes first order Fermi acceleration. The time evolution of the particle distribution and the associated synchrotron emission has been calculated for an energy dependent diffusion coefficient. When the emitting region is not spatially resolved, the spectrum is a power-law with an exponential turnover in frequency. With increasing time, the power-law and the turnover extend to higher frequencies. To test the model, observations at three or more frequencies should be made of time-resolved flux increases from the optically thin nonthermal emission region in variable active galactic nuclei. Existing data that can be used to test the model are scarce but offer qualitative support.

Bregman and M. Roberts (NRAO) studied the HI properties of cooling flow elliptical galaxies. The Arecibo 305 m radio telescope was used to make 21 cm measurements of NGC 4406, an elliptical galaxy containing $10^{10} M_\odot$ of hot diffuse gas. The HI decreases by a factor of 3 one beam width from the center (3.5 arcmin, or 20.4 kpc for $d = 20$ Mpc) and by an order of magnitude two beam widths from the center. Excess HI emission is seen in the X-ray tail, but not in dust-rich regions. The HI measurements do not support the suggestion that the X-ray tail is hot gas being stripped from the galaxy. The velocities of the peaks of the emission differ by less than 20 km/s for observations separated by more than 40 kpc, indicating that the HI has little rotation. Infall is also inconsistent with the line profiles, and we argue that random motion of HI clouds is the probable origin of the HI profile shapes. The properties of the HI gas agree with expectations of the cooling flow model in which cold gas is produced in situ as the hot gas radiatively cools.

Sarazin and G. Ashe (an undergraduate astronomy major supported during a summer on the NASA grant) calculated steady-state cooling flow models for the hot gas in normal elliptical galaxies, including the loss of X-ray emitting gas through inhomogeneous cooling. Since this cool gas may eventually form into stars, they refer to this process as "star formation". They find that the star-forming cooling flow models have smaller sonic radii, smaller inflow rates in their central regions, lower densities, and higher temperatures than homogeneous non-star-forming models. The star-forming models have higher velocities in the outer regions and lower velocities in the inner regions. Most of these differences are pronounced only in the central regions of the galaxy. The star-forming models also have lower X-ray luminosities (by a factor of at most 2.6), and this brings their luminosities into better agreement with the average observed X-ray luminosities of elliptical galaxies. However, there is large dispersion in the observed X-ray luminosities of ellipticals, and this cannot be explained by variations in the efficiency of star formation. The star-forming models have X-ray surface brightness profiles which are much less centrally peaked than the non-star-forming models, and models with very efficient star formation are in reasonable agreement with the observed surface brightness profiles of ellipticals. The integrated X-ray spectra of star-forming and non-star-forming models are rather similar. On the other hand, the X-ray spectra of the outer regions of the star-forming models have much stronger soft X-ray line emission, and this could be used to test between these two classes of models.

Sarazin and Ray White (University of Alabama) have studied the wide dispersion in the X-ray luminosities of elliptical galaxies of a given optical luminosity. It is known that the X-ray luminosities of elliptical galaxies are strongly correlated with their optical luminosity, but there is a considerable scatter in this relationship. They have searched for a correlation between the X-ray luminosity and many intrinsic properties of elliptical galaxies, and they have found no strong correlations. Instead, they find that the X-ray luminosities correlate strongly with environment. The less luminous X-ray ellipticals are found in dense environments; that is, for a given optical luminosity, the X-ray luminosity of an elliptical anticorrelates with the presence of many neighboring galaxies. Within the Virgo cluster, they also find that the X-ray luminosity increase with distance from the cluster center. This suggests that the amount of hot gas in elliptical galaxies is controlled, at least in part, by the stripping of gas due to ram pressure ablation or collisional stripping.

Hot Gas and Galaxy Formation

Chevalier and E. Lufkin (a graduate student on the grant) examined the spherical collapse of a gas cloud initially in hydrostatic equilibrium using self-similar solutions. They assumed an initial power law density distribution and that some energy loss of cooling initiates the collapse. The continued collapse can occur on a hydrodynamic timescale (hydro-regulated) or be regulated by the cooling process (cooling-regulated). The hydrodynamic timescale is roughly equal to the free-fall time. Collapses under self-gravity are generally hydro-regulated, while collapses in an external gravitational field are generally cooling-regulated. The collapse of gas clouds to form galaxies could occur on a hydrodynamic timescale only if the gas dominated the gravitational field and the inflow formed a central dominant mass. The likelihood of a collisionless component and the observation of extended mass distributions in galaxies implies that the collapse of a hot protogalactic cloud is cooling-regulated. Chevalier and Lufkin examined how our Galaxy might form from an initially smooth, hot cloud and showed that some nonlinear substructure must initially be present.

S. Murray (a post-doc on the grant) and D. Lin (U.C. Santa Cruz) have examined the diffusion of metals within protoglobular clusters The observed homogeneity in [Fe/H] among the stars within a typical globular cluster implies that the cluster stars were formed in well mixed protoglobular cluster clouds over a timescale short compared with that required for gas to recycle and self-enrich. Previous work has indicated that the protoclusters can form from primordial gas on a timescale comparable to the crossing time of the clusters in the galaxy and undergo star formation through fragmentation on a timescale comparable to both the internal dynamical timescale of the clusters and the stellar evolution timescale of upper main sequence stars. In their current this work, they examine various transport processes which may have affected the chemical homogeneity in the protocluster clouds. They find that the characteristic diffusion timescale associated with collisions between grains and gas atoms is considerably longer than that on which star formation is expected to occur. Collisions between large grains and gas atoms lead to mass segregation and metallicity gradients on a timescale comparable to the crossing time of the clusters in the Galaxy. One possible mechanism for inducing and maintaining chemical homogeneity is turbulent diffusion in the clouds. The mixing timescale required in this case is comparable to several internal dynamical timescales, longer than the evolutionary timescale of the most massive stars, and shorter than the Galactic orbital timescale of the clouds. Thus, metals in presently observed stars probably did not originate from upper main sequence stars of a coeval generation.

Hot Gas in Clusters of Galaxies

Balbus studied the effects of a magnetic field on the development of linear thermal instability in a hot plasma. He found that local condensational growth is possible for a class of short wavelength modes due to magnetic confinement of higher pressure regions. In regions of ordered magnetic fields within clusters, this effect may be of (destabilizing) importance if thermal conduction can be suppressed.

Balbus, Hawley and Eric Lufkin (graduate student) continued their work on the formation and evolution of finite-amplitude and finite-wavelength disturbances in cluster cooling flows perturbed by a single galaxy orbiting along the symmetry axis. They have performed two-dimensional time-dependent axisymmetric numerical simulations and found that for density and temperature profiles typical of a large cluster cooling flow, the perturbing galaxy excites nonlinear gravity modes which result in local density enhancements of order unity and fluid velocities in excess of 500 km s^{-1}.

Balbus and Murray (postdoc on the grant, now at Cambridge) completed a study of time dependent cluster cooling flows using a characteristic based scheme. They found that evolutionary effects may be important, because the effects tend to reproduce a linear mass accretion profile unrelated to any in situ cooling or deposition process.

Balbus and Soker have concluded a study of linear thermal instability in optically thin dynamical and static plasmas. Several new and fundamental results have been found. For example, they have shown that systems in both hydrostatic and thermal equilibrium are in general thermally stable if convectively stable, and vice-versa. This basic and important result went undiscovered for some 23 years since the original paper on thermal instability. Balbus and Soker have also examined dynamical flows in some detail. This work has been applied to the flow of hot x-ray emitting gas observed in the volume between the galaxies in richly populated clusters. It has been shown that these flows are considerably more stable than commonly thought. This has caused investigators to reconsider current theories of evolution of these hot plasmas.

Balbus and Soker concluded a study of the resonant interaction between the orbital motion of a galaxy in a cluster of galaxies and the buoyant oscillations of the hot X-ray emitting gas bound to the cluster. Such interactions excite internal gravity waves in the gas. (Internal gravity waves are well-known in oceanographic and atmospheric studies.) These waves represent the fundamental dynamical response of the gas to external forces with characteristic time scales of order galactic orbital periods. The presence of these waves has many consequences. The energy carried by these waves can be a significant source of drag for an orbiting galaxy. Angular momentum transport by the waves couples galactic orbital motion and the dynamics of the hot gas. Gravity waves propagate toward the central regions of the gas, where they are likely to grow to nonlinear amplitudes, and are perhaps associated with optical filamentary structure often observed near the center of clusters. The group velocity associated with internal gravity wave propagation is an important dispersive mechanism that limits the ability of thermal instabilities to grow in a hot, cooling plasma.

P. Becker (a post-doc on the grant) and Balbus have investigated relativistic particle transport in spherical background flows with momentum and spatially dependent diffusion coefficients. They have obtained results that describe the diffusion and first-order Fermi acceleration of relativistic particles in a gas of scatterers experiencing either inflow or outflow. Four qualitatively different regimes of behavior have been identified, depending on the sign of the velocity of the background plasma and the competition between advection and diffusion at large and small radii. Solutions have been obtained for the Green's function corresponding to monoenergetic particle injection at a thin shell. Particles propagating away from this shell always gain energy if the scattering centers are inflowing; otherwise they lose energy. Results have been used to calculate the synchrotron spectra produced by relativistic electrons accelerated in cooling flows in clusters of galaxies. Particle acceleration in converging cooling flows may provide a natural explanation for the extended ($\gtrsim$ 100 kpc) radio halos observed around the central galaxy in a number of cooling-flow clusters, most notably Perseus. The results of the transport theory can also be applied to the broadening and redshifting of line profiles in supernova winds and to the production of asymmetric line profiles in quasars.

Bregman and L. David (former NASA theory post-doc now at Harvard/CFA) applied numerical hydrodynamics to investigate the effects of heat conduction and magnetic fields on the growth of thermal instabilities in cooling flows. For magnetic field strengths of about 1 μG (similar to that in intracluster gas), magnetic pressure forces can completely suppress shocks from forming in thermally unstable entropy perturbations with initial length scales as large as 20 kpc, even for initial amplitudes as great as 60%. The suppression of shock formation in cooling condensations significantly reduces the predicted luminosity of optical and ultraviolet emission lines produced as thermally unstable gas cools and decouples from a cooling flow. They find that perturbations with initial amplitudes of 50% and initial magnetic field strengths of 1 μG cool to 10^4 K on a time scale which is only 22% of the initial instantaneous cooling time. Nonlinear perturbations can condense out of cooling flows on a time scale substantially less than the time required for linear perturbations and produce significant mass deposition of cold gas while the accreting intracluster gas is still at large radii. Our models with heat conduction indicate that in order for entropy perturbations to condense out of cooling flows, the magnetic fields must be sufficiently tangled to reduce the Spitzer conductivity by a factor of approximately 100. Observational consequences have been considered of condensations in cooling flows. It is found that Faraday rotation can be generated by cold, dense, high magnetic pressure clouds lying along the line of sight to cluster radio sources.

Bregman and David also examined whether viable models could be found for cluster cooling flows that avoided the prediction of the standard model that gas was cooling at enormous rates. The two most important observations that a model must reproduce is the observed temperature gradient and the lack of young stars that would be produced if cooled gas normally formed stars. In the first model considered, drag heating by galaxies reheats the cluster gas and also suppresses thermal instabilities in certain temperature regimes. Numerical hydrodynamic simulations show that it is possible to produce the observed temperature gradient while significantly reducing the cooling rate for the gas, but only for a narrow range of the galaxy heating parameter. In another model, the gas cools and begins to form stars, which lead to supernovae that reheat the cooled gas to the ambient cluster temperature. This model is viable if only high-mass stars are formed and if the supernovae are subluminous.

Bregman, B. McNamara (a graduate student), and O'Connell investigated the infrared properties of cooling flow systems and the behavior of dust in a hot environment. IRAS strip-scans were used to study the infrared emission properties of 27 dominant galaxies that lie in the center of clusters rich in hot gas. In this sample, 30% of the objects were detected at 12/25 microns while 46% were detected at 60/100 microns. The ratio of the infrared to optical flux densities is an order of magnitude greater than for elliptical and S0 galaxies. The presence of infrared emission is not obviously correlated with the redshift z, the optical magnitude m_V, the absolute magnitude M_V, the presence of young stellar populations, emission line gas, the X-ray luminosity, or the cooling rate of hot gas $\dot{M}$. The infrared luminosities, which are comparable to the X-ray and blue optical luminosities ($10^{44} - 10^{45}\,\mathrm{ergs\,s^{-1}}$), imply dust masses of $(0.3-3) \times 10^7 (T_{dust}/30\,\mathrm{K})^{-5.9}\,M_\odot$, and gas to dust ratios $< 1000(T_{dust}/30\,\mathrm{K})^{-5.9}$. The dust grains are probably heated by collisions with electrons in the X-ray emitting gas, a process that also causes grain destruction. A possible supply of dust is stellar mass loss, although this may not be entirely adequate to balance the inferred destruction rate.

McNamara and O'Connell completed their study of the spectra of cD galaxies in cooling flows. They present $\lambda\lambda$3400-5100 spectrophotometry of the nuclei of 13 galaxies in cluster cooling flows with estimated cooling rates of $\dot{M} \sim$ 5-350 $M_\odot$/yr. They find spectral anomalies, with respect to a control sample, in 8 of the 13 objects in the form of strong [O II] emission and/or excess flux in the 3500-4000 Å continuum. The anomalies tend to be associated with larger predicted cooling flow effects, though the relationship is not very tight. The continuum anomalies are apparently due to the presence of massive OB stars that have formed from the cooling flows, rather than nonthermal radiation or metallicity effects. In no case, however, is the excess consistent with a 100% efficient conversion to stars with a normal IMF.

McNamara, Bregman, and O'Connell searched for H I in 14 cluster cooling flows with the Arecibo and the Green Bank 300 ft. radio telescopes. They detected H I in absorption against the radio continuum sources near the centrally-dominant galaxies in the clusters 2A0335+096 and MKW3s. The H I absorption features are redshifted with respect to the central galaxies, indicating that the H I is probably falling toward the central galaxies. H I was not detected in emission. Upper limits to the H I-to-dust ratio in four objects are found to be consistent with the Galactic mean gas-to-dust ratio. These H I detections, and one for NGC 1275 reported by other groups, are the most direct evidence to date that the gas in cooling flows reaches the central galaxy.

McNamara and O'Connell completed two analyses of the properties of galaxies in the center of massive cooling flows in clusters of galaxies. X-ray observations imply that mass drop-out from the flows occurs at the rate of several hundred solar masses per year in these galaxies. The only plausible sink for this inflow is star formation. There is strong corroborative optical evidence for the existence of the cooling flows, but in no case does the amount of observed star formation correspond to more than about 30% of the predicted rate if the initial mass function is normal. The only viable repository for the inflowing mass therefore appears to be in the form of very low mass stars or smaller objects—*i.e.* "brown dwarfs" or "jupiters". O'Connell and McNamara examined in some detail the prospects for direct detection of such objects and concluded that they are not good with current optical or infrared instrumentation.

Sarazin has shown that X-ray absorption lines may be detectable from clusters of galaxies, if there is a background quasar projected behind the cluster. The detection of such a resonant absorption line and of the emission from the cluster in the same line would allow the distance to the cluster to be determined, independent of the standard extragalactic distance scale. The basics idea is simple; the absorption from the gas is independent of distance as long as the cluster is in front of the quasar. The flux of X-ray line emission depends inversely on the square of the distance, so a comparison of the absorption and emission gives an estimate of the distance. This technique is very similar to the distance determination based on the Zeldovich–Sunyaev microwave diminution. Sarazin found that the required X-ray observations should be possible with AXAF, but that it will be difficult to attain the level of accuracy required to provide a definitive determination of the Hubble constant.

Sarazin and Graney have calculated the predicted luminosity and the surface brightness profiles of the optical coronal emission lines for models of cooling flows in galaxy clusters and in individual elliptical galaxies. The surface brightness profiles of the lines directly indicate where gas is cooling below X-ray emitting temperatures. In homogeneous cooling flow models in which all of the gas flows into the central regions, the coronal lines are very centrally concentrated. For inhomogeneous models in which gas cools out of the flow at large radii, the surface brightness profiles of the coronal lines are more extended, and the central surface brightness is much lower. Existing observations apparently rule out homogeneous cooling flow models for several clusters if the cooling rates inferred from X-ray observations are correct. If gas is indeed cooling at these rates, it should be possible to detect optical coronal emission lines in many cooling flow clusters. If the lines are not detected, it would establish unambiguously that gas is not cooling at the rates inferred from the X-ray observations. If the lines are detected, their spatial distribution will show directly where the cooling gas is being deposited.

Sarazin and R. White (Univ. of Alabama) have compared the X-ray images of M87-Virgo and NGC1275/Perseus clusters to models for cluster cooling flows which include star-formation. X-ray observations indicate that M87/Virgo and NGC1275/Perseus have cooling flows which are associated with accretion rates of $\sim 20 - 30$ and $\sim 300 - 500\, M_\odot\, \mathrm{yr}^{-1}$, respectively. By deconvolving X-ray surface brightness profiles of these cooling flow clusters, a number of authors have found the accretion rates to decrease inwards, suggesting that the bulk of the mass flux is dropping out (presumably to form stars). However, cooling flow models which assume the mass flux is constant with radius (so there is no star formation) have never been calculated self-consistently for these objects. Sarazin and White determined whether star formation is necessarily occurring in these cooling flows by calculating constant-mass-flux models for all reasonable parameter space. They assumed that the inflow was steady-state, and that collisional heating and thermal conduction were insignificant. They found no constant-mass-flux models which were consistent with all of the relevant observations, so concluded that mass is indeed dropping out of these cooling flows. They then considered a variety of star-forming models in which the X-ray emission due to cooling condensates is taken into account. For M87/Virgo they could find models in which the mass flux vanishes by the center. In NGC1275/Perseus, they find that the mass flux diminishes by $\lesssim 40\%$ by the time the flow reaches ~ 20 kpc (the effective inner limit of the X-ray surface brightness data). The remaining mass flux within 20 kpc was $\sim 300\, M_\odot\, \mathrm{yr}^{-1}$, which is unacceptably high for the flow temperatures we derive.

Sarazin and Wise have calculated the effects of electron scattering on cluster cooling flows. Cluster cooling flows have electron scattering optical depths which are estimated to be about 10^{-2}. Many of the cluster dominant galaxies centered in cluster cooling flows have active nuclei, and about 1% of the luminosity from the active nuclei should appear as diffuse, scattered radiation. Due to significant amounts of diffuse emission in other wavebands, this scattered radiation is most likely to be observable at radio wavelengths. Distinguishing between scattered radiation and other sources of diffuse emission poses a serious problem. However, the scattered emission should have the same spectral index as the central source, should be axisymmetric, and has a surface brightness distribution which can be predicted from the observed X-ray surface brightness. They show that detection of this scattered radiation can provide a measure of the distance to the cluster that is independent of the Hubble constant. Observations of the scattered surface brightness profile can also be used to test for clumpiness in the gas, for variations in the central radio source on time scales $\lesssim 10^5$ years, and for the degree of beaming of radiation from the central source.

Sarazin and Wise also studied the relationship between BL Lacertae (BL Lac) objects and Fanaroff-Riley type I (FR I) radio galaxies. They showed that the strong beams of radiation present in BL Lac's and FR I's will be scattered and made visible by cooling flow gas.

Soker, Bregman, and Sarazin have shown that the nonlinear perturbations which lead to thermal instabilities in cooling flows might start as blobs of interstellar gas which are stripped out of cluster galaxies. Assuming that most of the gas produced by stellar mass loss in cluster galaxies is stripped from the galaxies, the total rate of such stripping is roughly $\dot{M}_{ISM} \sim 100\, M_\odot\, \mathrm{yr}^{-1}$, which is similar to the rates of cooling in cluster cooling flows. It is possible that a substantial portion of the cooling gas originates as blobs of interstellar gas stripped from galaxies. The magnetic fields within and outside of the low entropy perturbations may help to maintain their identities, by suppressing both thermal conduction and Kelvin-Helmholtz instabilities. Inhomogeneities in the intracluster medium caused by the stripping of interstellar gas from galaxies can have a number of other effects on clusters. These density fluctuations may disrupt the propagation of radio jets through the intracluster gas, which may be one mechanism for producing Wide-Angle-Tail radio galaxies.

Soker and Sarazin have studied the effects which intracluster magnetic field can have on cooling flows in clusters. Even a very weak magnetic field, if it is tangled on small scales, can effectively inhibit transport processes in the gas, such as thermal conduction, viscosity, and the settling of heavy ions. Estimates and limits on the strength of the magnetic fields in clusters suggest that the field is *not* dynamically important there. However, when gas cools and flows into the center of cooling flow clusters, the magnetic pressure is greatly increased by the compression and shear in the flow. They show that the magnetic field may become very important in the inner regions of cluster cooling flows. The magnetic pressure becomes comparable to the thermal pressure within a radius of typically $1 - 10$ kpc. Within this region, reconnection of the magnetic field becomes efficient and magnetic energy is released at a rate of $10^{41} - 10^{43}$ erg s^{-1}. Such models predict large values for the Faraday rotation of central radio sources in clusters.

Publications

Balbus, S. A. "On Magnetothermal Instability in Cluster Cooling Flows,", *Astrophysical Journal*, **372**, 25 (1991).

Balbus, S. A., "Large Scale Gasdynamics of Disk Galaxies," in *Proceedings of the Second Wyoming Meeting on Interstellar Processes: Interstellar Media in External Galaxies*, 305 (1990).

Balbus, S. A., "Local Gasdynamical Stability and Substructure in Spiral Arms", *Astrophysical Journal*, **324**, 60 (1988).

Balbus, S. A., "On Thermal Instability and Hydrostatic Equilibrium in Cooling Flows," *Astrophysical Journal*, **328**, 395 (1988).

Balbus, S. A., "Substructure in Spiral Arms," in *The Outer Galaxy*, eds. F. J. Lockman and L. Blitz (New York: Springer-Verlag), 138 (1988).

Balbus, S. A., and Hawley, J. F., "A Powerful Local Shear Instability in Weakly Magnetized Disks. I. Linear Analysis," *Astrophysical Journal*, **376**, 214 (1991).

Balbus, S. A., and Hawley, J. F., "A Powerful Local Shear Instability in Weakly Magnetized Disks. II. Nonlinear Evolution," *Astrophysical Journal*, **376**, 223 (1991)

Balbus, S. A., and Soker, N., "Theory of Local Thermal Instability in Spherical Systems," *Astrophysical Journal*, **341**, 611 (1989).

Balbus, S. A., and Soker, N., "Resonant Excitation of Internal Gravity Waves in Cluster Cooling Flows," *Astrophysical Journal*, **357**, 353 (1990).

Balbus, S. A., and Soker, N., "Theory of Local Thermal Instability in Spherical Systems," in *High Resolution X-ray Spectroscopy of Cosmic Plasmas*, IAU Colloquium No. 115, eds. P. Gorenstein and M. V. Zombeck, (Kluwer: Dordrecht), 44 (1990).

Becker, P., and Balbus, S. A., "Fermi Acceleration in Cooling Flows," *Astrophysical Journal*, submitted.

Blank, D. L., and Soker, N., "Evolution Sequence of Seyfert Galaxies," in *Proceeding of the Georgia State University Conference on Active Galactic Nuclei*, eds. H. R. Miller and P. J. Wiita, p. 427 (1988).

Borkowski, K. J., Balbus, S. A., Fristrom, C. C., "Radiative Magnetized Thermal Conduction Fronts," *Astrophysical Journal*, **355**, 501 (1990).

Borkowski, K. J., Balbus, S. A., Fristrom, C. C., "Radiative Thermal Conduction Fronts," in *The Interstellar Medium in External Galaxies*, Proc. The Second Wyoming Conference, ed. D. Hollenbach and H. Thronson (Washington: NASA), 177 (1990).

Borkowski, K. J., Sarazin, C. L., and Soker, N., "Interaction of Planetary Nebulae with the Interstellar Medium," *Astrophysical Journal*, 360, 173 (1990).

Borkowski, K. J., Sarazin, C. L., and Soker, N., "Interaction of Planetary Nebulae with the Interstellar Medium," *Bulletin American Astronomical Society*, **22**, 751 (1990).

Bregman, J. N., "A Theoretical Understanding of Hot Gas Around Galaxies," in *Hot Thin Plasmas in Astrophysics*, ed. R. Pallavicini (Dordrecht: Reidel), 247 (1988).

Bregman, J. N., and Boisseau, J. R., "The Radiative Signature of the Shock Acceleration Process in Active Galactic Nuclei," *Astrophysical Journal*, **347**, 118 (1989).

Bregman, J. N., *et al.* "Multifrequency Observations of BL Lacertae," *Astrophysical Journal*, **352**, 574 (1990).

Bregman, J. N., and David, L. P., "Alternative Cooling Flow Models," *Astrophysical Journal*, **341**, 49 (1989).

Bregman, J. N., and David, L. P., "Heat Conduction In Cooling Flows," *Astrophysical Journal*, **326**, 639 (1988).

Bregman, J. N., and Hogg, D. E., "A Search For CO Emission In Cooling Flows," *Astronomical Journal*, **96**, 455 (1988).

Bregman, J. N., McNamara, B. R., and O'Connell, R. W., "Far Infrared Emission from Dominant Cluster Galaxies," *Astrophysical Journal*, **351**, 406 (1990).

Bregman, J. N., and Roberts, M. S., "HI in The Giant Elliptical Galaxy NGC 4406," *Astrophysical Journal*, **362**, 468 (1990).

Bregman, J. N., Roberts, M. S., and Giovanelli, R., "HI In Giant Elliptical Galaxies With Cooling Flows," *Astrophysical Journal (Letters)*, **330**, L93 (1988).

Chevalier, R. A., "Circumstellar and Interstellar Interaction Around SN1987A," in *Supernovae*, ed. S. E. Woosley (Berlin: Springer), in press (1990).

Chevalier, R. A., "Late Evolution of SN1987A," *Proceeding Astronomical Society of Australia*, **7**, 513 (1988).

Chevalier, R. A., "Neutron Star Accretion in a Supernova," *Astrophysical Journal*, **346**, 847 (1989).

Chevalier, R. A., "Supernova 1987A: The Envelope Thickens," *Nature*, **339**, 96 (1989).

Chevalier, R. A., "Supernova Remnants: Theory and Interpretation," in *The Reference Encyclopedia of Astronomy and Astrophysics*, ed. S. P. Maran (New York: Van Nostrand), in press (1990).

Chevalier, R. A., "Supernovae and Supernova Remnants at High Energies," in *High Energy Astrophysics in the 21st Century*, ed. P. Joss (Washington: NASA), 38 (1990).

Chevalier, R. A., "Supernovae and Supernova Remnants at Low Frequencies," in *Low Frequency Astrophysics from Space*, ed. N. Kassim and K. Weiler (Berlin: Springer), in press (1990).

Chevalier, R. A., "Supernovae and Supernova Remnants in Starbursts," in *Massive Stars in Starbursts* ed. by C. Leitherer, N. Walborn, T. Heckman, and C. Norman (Cambridge: Cambridge Univ. Press), p. 169 (1991).

Chevalier, R. A., "Supernovae and the Interstellar Medium," in *Supernovae* ed. by J. Audouze, S. Bludman, R. Mochkovitch, and J. Zinn-Justin (Amsterdam: Elsevier), in press (1991)

Chevalier, R. A., "The Early Evolution of Supernova Remnants," in *IAU Colloq. 101, Supernova Remnants and the Interstellar Medium*, ed. R. S. Rogers and T. L. Landecker (Cambridge: Cambridge Univ. P.), 31 (1988).

Chevalier, R. A., "The Evolution of Cooling Flows: II. Galaxies and Galaxy Formation," *Astrophysical Journal*, **329**, 16 (1988).

Chevalier, R. A., "The Interaction of Supernova 1987A with Dense Circumstellar Gas," *Nature*, **332**, 514 (1988).

Chevalier, R. A., "The Interaction of Supernovae with Circumstellar Matter," in *Supernovae*, ed. A. G. Petschek, (Berlin: Springer) 91 (1990).

Chevalier, R. A., "The Radio Evolution of SN 1987A" *Nature*, submitted (1991).

Chevalier, R. A., "The Theory of Supernova Remnants and the Hot Interstellar Medium," in *Hot Thin Plasmas in Astrophysics*, ed. R. Pallavicini (Dordrecht: Reidel), 213 (1988).

Chevalier, R. A., "Theory of Supernova Remnants," in *Proc. of Beijing Workshop on Supernovae and Supernova Remnants* ed. by Ma Er (Beijing), in press (1991)

Chevalier, R. A., and Emmering, R. T., "Illuminating a Red Supergiant Wind around SN1987A," *Astrophysical Journal Letters*, **342**, L75 (1989).

Chevalier, R. A., and Emmering, R. T., "The Interstellar Light Echoes Around SN1987A," *Astrophysical Journal (Letters)*, **331**, L105 (1988).

Chevalier, R. A., and Liang, E., "The Interaction of Supernovae with Circumstellar Bubbles," *Astrophysical Journal*, **344**, 332 (1989).

Chevalier, R. A., and Lufkin, E. A., "The Gravitational Collapse of Gaseous Spheres and Galaxy Formation," *Astrophysical Journal*, **356**, 41 (1990).

Chevalier, R. A., and Plait, P. C., "The Nature of S Andromedae (SN1885A)," *Astrophysical Journal (Letters)*, **331**, L109 (1988).

Chevalier, R. A., and Seward, F. D., "Supernovae and Supernova Remnants," in *Multiwavelength Astrophysics*, ed. F. Cordova (Cambridge: C. U. Press) 235 (1988).

Chevalier, R. A., and Soker, N., "Asymmetric Envelope Expansion of SN1987A," *Astrophysical Journal*, **341**, 867 (1989).

Chiang, W. H., and Bregman, J. N., "A Model for the Interaction between Stars and Gas in the Interstellar Medium," *Astrophysical Journal*, **328**, 427 (1988).

David, L. P., and Bregman, J. N., "The Effects of Magnetic Fields on the Growth of Thermal Instabilities In Cooling Flows," *Astrophysical Journal*, **337**, 97 (1989).

David, L. P., Bregman, J. N., and Seab, C. G., "Thermal Instabilities In Cooling Flows," *Astrophysical Journal*, **329**, 66 (1988).

Dgani, R., Livio, M., and Soker, N., "On the Stream-Accretion Disk Interaction: Response to the Increased Mass Transfer Rate", *Astrophysical Journal*, **336**, 350 (1989).

Emmering, R. T., and Chevalier, R. A., "Circumstellar Infrared and Scattered Light Echoes from SN 1987A", *Astrophysical Journal*, **338**, 388 (1989)

Emmering, R. T., and Chevalier, R. A., "Infrared Supernova Light Curves and Asymmetric Stellar Mass Loss," *Astronomical Journal*, **95**, 152 (1988).

Emmering, R. T., and Chevalier, R. A., "The Intrinsic Luminosity and Initial Period of Pulsars", *Astrophysical Journal*, **345**, 931 (1989).

Fransson, C., and Chevalier, R. A., "Late Emission from Supernovae: A Window on Stellar Nucleosynthesis," *Astrophysical Journal*, **343**, 323 (1989).

Gaetz, T. J., Edgar, R. J., and Chevalier, R. A., "Stability of Radiative Shocks with Time Dependent Cooling," *Astrophysical Journal*, **329**, 927 (1988).

Gott, J. R., Miller, J. M., Thuan, T. X., Schneider, S. E., Weinberg, D. H., Gammie, C., Polk, K., Vogeley, M., Jeffrey, S., Bhavsar, S. P., Melott, A. L., Giovanelli, R., Haynes, M. P., Tully, R. B., and Hamilton, A. J. S., "The Topology of Large-Scale Structure. III. Analysis of Observations," *Astrophysical Journal*, **340**, 625 (1989).

Graney, C. M., and Sarazin, C. L., "Optical Coronal Emission Lines from Equilibrium and Cooling Plasmas," *Astrophysical Journal*, **364**, 561 (1990).

Houck, J. C., and Bregman, J. N., "Low Temperature Galactic Fountains," *Astrophysical Journal*, **352**, 506 (1990).

Huchtmeier, K., Bregman, J. N., Hogg, D. E., and Roberts, M. S., "Detection of CO in the Elliptical Galaxy NGC 4472," *Astronomy and Astrophysics*, **198**, L17 (1988).

Kochanek, C. S., and Hawley, J. F., "Hollow Conical Jet Models for SS 433: A Paradigm Lost?" *Astrophysical Journal*, **350**, 561 (1990).

Livio, M., and Soker, N., "The Common Envelope Phase in the Evolution of Binary Stars", *Astrophysical Journal*, **329**, 764 (1988).

McNamara, B. R., Bregman, J. N., and O'Connell, R. W., "HI Absorption toward Cooling Flows in Clusters of Galaxies," *Astrophysical Journal*, **360**, 20 (1990).

McNamara, B. R., and O'Connell, R. W., "Star Formation in Cooling Flows in Clusters of Galaxies", *Astronomical Journal*, **98**, 2018 (1989).

Murray, S. D., and Balbus, S. A., "Characteristic Based Models for the Evolution of Cooling Flows,", *Astrophysical Journal*, submitted (1991)

Murray, S. D., and Lin, D. N. C., "On the Origin of Metal Homogeneities in Globular Clusters," *Astrophysical Journal*, **357**, 105 (1990).

Murray, S. D., and Lin, D. N. C., "The Formation of Coronal Regions in Accretion Disks," *Astrophysical Journal*, submitted (1991).

O'Connell, R. W., and McNamara, B. R., "Evidence for Star Formation in Cooling Flows", in *Cooling Flows in Clusters and Galaxies*, ed. A. C. Fabian (Dordrecht: Kluwer), p. 103 (1988).

O'Connell, R. W., and McNamara, B. R., "The Fate of Matter in Cooling Flows", *Astronomical Journal*, **98**, 180 (1989).

Plait, P., and Soker, N., "On the Evolution of the Planetary Nebula NGC 6826," *Astronomical Journal*, **99**, 1883 (1990).

Ryden, B. S., Melott, A. L., Craig, D. A., Gott, J. R., Weinberg, D. H., Scherrer, R. J., Bhavsar, S. B., and Miller, J. M., "The Area of Isodensity Contours in Cosmological Models and Galaxy Surveys," *Astrophysical Journal*, **340**, 647 (1989).

Sarazin, C. L., "Cooling Flows and X-Ray Emission in Early-Type Galaxies," in *The Interstellar Medium of External Galaxies*, ed. by H. A. Thronson, Jr. and J. M. Shull (Dordrecht: Kluwer), 201 (1990).

Sarazin, C. L., "Cooling Flows in Clusters of Galaxies," in *Frontiers of X-ray Astronomy*, ed. by Y. Tanaka and K. Koyama (Tokyo: Universal Academy), in press.

Sarazin, C. L., "Properties of Clusters of Galaxies", in *Cooling Flows in Galaxies and Clusters*, ed. by A. Fabian (Kluwer: Dordrecht), 1 (1988).

Sarazin, C. L., "The Intracluster Medium," in *Clusters and Superclusters of Galaxies*, ed. by A. C. Fabian (Dordrecht: Kluwer), in press.

Sarazin, C. L., "Using X-ray Absorption Lines to Determine the Distances to Clusters of Galaxies," *Astrophysical Journal*, **345**, 12 (1989).

Sarazin, C. L., "X-ray Spectra of Clusters of Galaxies," in *Proceedings of I.A.U. Colloquium 115: High Resolution X-ray Spectroscopy of Cosmic Plasmas*, ed. by P. Gorenstein and M. Zombeck (Kluwer: Dordrecht), 209 (1990).

Sarazin, C. L., "X-ray Emission from Clusters of Galaxies", (Cambridge University Press: Cambridge) (1988)

Sarazin, C. L., and Ashe, G. A., "Steady-State Cooling Flow Models with Gas Loss for Normal Elliptical Galaxies," *Astrophysical Journal*, **345**, 22 (1989).

Sarazin, C. L. and Graney, C. M., "Optical Coronal Emission Lines from Cooling Flows in Elliptical Galaxies and Galaxy Clusters," *Astrophysical Journal*, **375**, 532 (1991)

Sarazin, C. L., and White, R. E. III, "The X-ray Emission of Normal Elliptical Galaxies: Steady State Cooling Flow Models", *Astrophysical Journal*, **331**, 102 (1988).

Sarazin, C. L., and White, R. E. III, "Environmental Effects and the Gaseous Content of Early-Type Galaxies," in *Proceedings of the Sesto Pusteria Workshop on Superclusters and Clusters of Galaxies and Environmental Effects*, ed. by G. Giuricin, F. Mardirossian, and M. Mezzetti, 103 (1991).

Sarazin, C. L., and White, R. E. III, "The X-ray Emission of Normal Elliptical Galaxies and their Environment," in *Windows on Galaxies*, ed. by G. Fabbiano, J. S. Gallagher, and A. Renzini (Dordrecht: Kluwer), 279 (1990).

Sarazin, C. L., and White, R. E. III, "The X-ray Emission of Normal Elliptical Galaxies: Steady State Cooling Flow Models," *Astrophysical Journal*, **331**, 102 (1988).

Sarazin, C. L. and Wise, M. W., "BL Lac Objects, FR I Radio Sources, and Cluster Cooling Flows," in *Galaxy Environments and the Large Scale Structure of the Universe*, ed. by G. Giuricin, F. Mardirossian, and M. Mezzetti, 149 (1991).

Sarazin, C. L. and Wise, M. W., "Iron Line Diagnostics in Elliptical Galaxies and Cluster Cooling Flows," in *Proceedings of the Varenna Workshop: Iron Line Diagnostics in X-ray Sources*, ed. by A. Treves (Berlin: Springer-Verlag), 57 (1991).

Soker, N., "Early Shaping of Asymmetrical Planetary Nebulae", *Astrophysical Journal*, **340**, 927 (1989).

Soker, N., "Early Shaping of Asymmetrical Planetary Nebulae," in *Proceeding of the IAU Colloquium No. 106 on Evolution of Peculiar Red Giants Stars*, eds. Hollis R. Johnson and Ben Zuckerman (Cambridge: Cambridge Univ. Press), p. 232 (1989).

Soker, N., "On the Formation of Ansae in Planetary Nebulae," *Astronomical Journal*, **99**, 1869 (1990).

Soker, N., Borkowski, K. J., and Sarazin, C. L., "Interaction of Planetary Nebulae with the Interstellar Medium: Theory," *Astronomical Journal*, **102**, 1381 (1991).

Soker, N., Bregman, J. N., and Sarazin, C. L., "ISM Stripping from Cluster Galaxies and Cooling Flows," in *Proceedings of the Wyoming Conference on the Interstellar Medium of External Galaxies*, ed. by H. A. Thronson, Jr. and J. M. Shull (Washington: NASA), 203 (1990).

Soker, N., Bregman, J. N., and Sarazin, C. L., "Stripped Interstellar Gas in Cluster Cooling Flows," *Astrophysical Journal*, **368**, 341 (1991).

Soker, N., and Livio, M., "Interacting Winds and the Shaping of Planetary Nebulae", *Astrophysical Journal*, **339**, 268 (1989).

Soker, N., O'Dea, C. P., and Sarazin, C. L., "Numerical Simulations of the Bending of Narrow-Angle-Tail Radio Jets by Ram Pressure or Pressure Gradients", *Astrophysical Journal*, **327**, 627 (1988).

Soker, N., and Sarazin, C. L., "Cooling Flows and the Stability of Radio Jets," *Astrophysical Journal*, **327**, 66 (1988).

Soker, N., and Sarazin, C. L., "The Role of Magnetic Fields in Cluster Cooling Flows", in *Cooling Flows in Galaxies and Clusters*, ed. by A. Fabian (Kluwer: Dordrecht), 367 (1988).

Soker, N., and Sarazin, C. L., "The Role of Magnetic Fields in Cluster Cooling Flows," *Astrophysical Journal*, **348**, 73 (1990).

White, R. E. III and Sarazin, C. L., "Apparent Environmental Influence on Early-Type Galaxy X-ray Halos," in *Proceedings of the Sesto Pusteria Workshop on Superclusters and Clusters of Galaxies and Environmental Effects*, ed. by G. Giuricin, F. Mardirossian, and M. Mezzetti, 131 (1991).

White, R. E. III and Sarazin, C. L., "Evidence for Environmental Effects on Early-type Galaxy X-ray Halos," *Astrophysical Journal*, **367**, 476 (1991).

White, R. E. III, and Sarazin, C. L., "Accounting for the Dispersion in the X-ray Properties of Early-Type Galaxies," in *Proceedings of the Wyoming Conference on the Interstellar Medium of External Galaxies*, ed. by H. A. Thronson, Jr. and J. M. Shull (Washington: NASA), 204 (1990).

White, R. E. III, and Sarazin, C. L., "Star Formation in the Cooling Flows of M87/Virgo and NGC1275/Perseus", *Astrophysical Journal*, **335**, 688 (1988).

Wise, M. W. and Sarazin, C. L., "Electron Scattering of Beamed Radiation from AGN in Cluster Cooling Flows," in *Clusters and Superclusters of Galaxies*, ed. by M. M. Colless, A. Babul, A. C. Edge, R. M. Johnstone, and S. Raychaudhary (Cambridge: Institute of Astronomy), 153 (1991).

Wise, M. W. and Sarazin, C. L., "Using Electron Scattering to Probe the Environment of Cluster Cooling Flows," *Astrophysical Journal*, submitted (1991).

Wise, M. W., and Sarazin, C. L., "Charge Transfer and X-ray Emission from Supernova Remnants," *Astrophysical Journal*, **345**, 384 (1989).

Wise, M. W., and Sarazin, C. L., "Electron Scattering and the Distances to Cluster Cooling Flows," *Astrophysical Journal*, **363**, 344 (1990).

Wise, M. W., and Sarazin, C. L., "Electron Scattering and the Distances to Cluster Cooling Flows," *Bulletin American Astronomical Society*, **21**, 1169 (1989).

Woosley, S. E., and Chevalier, R. A., "Was the Millisecond Pulsar in SN1987A Spun Up or Born Spinning Fast?" *Nature*, **338**, 321 (1989).