**McMaster University**
**Department of Physics and Astronomy**
*Hamilton, Ontario L8S 4M1 Canada*

[S0002-7537(93)04731-6]

The following report summarizes the activities of the Astronomy and Astrophysics Group of the Department over the period January through October 2000. Our last report appeared in 1999 and is posted on the Web.

Current information about our people and facilities, including our annual report, can be obtained from our Department Website, http://www.physics.mcmaster.ca

## 1. PERSONNEL

### 1.1 Faculty

The astrophysics faculty include Professors Couchman, Harris, Pudritz, Sutherland, Welch, and Associate Professor Wilson.

**Hugh Couchman** carries out research in theoretical cosmology and the numerical simulation of galaxy formation through high performance computing. He is a member of CITA Council and is developing several initiatives concerned with computing infrastructure in Canada, including chair of the ad hoc computing committee of the Long Range Planning Panel for Canadian Astronomy; chair of the Theory and Computation subcommittee of the Canadian Astronomical Society; and a principal author of succerssful proposals for SHARC-Net, a ''Top-500'' high performance computing network in Southern Ontario.

**William Harris** carries out observational studies of globular clusters and the distance scale. During year 2000 he continued as a member of the Board of Directors of the Canada-France-Hawaii Telescope; the Long Range Planning Panel for Canadian Astronomy; and completed a term on the Canadian Steering Committee for the Gemini telescopes.

**Ralph Pudritz** is a theoretical astrophysicist who carries out research in star formation in the galaxy, as well as in the context galaxy formation. During 2000 he continued as Chair of the NRC/NSERC/CASCA Long Range Planning Panel for Canadian Astronomy; its final report entitled ''*The Origins of Structure in the Universe: Canadian Astronomy and Astrophysics in the 21st Century*'' was published in October 1999, and officially released in both languages as well as in a bilingual Web version ( http://www.casca.ca/lrp) in May 2000. During the year he helped design and drive an outreach campaign to disseminate the results to the funding agencies, government, and media. He continued as a member of CITA Council until June 2000, and is currently a member of the Canadian Gemini Steering Committee and the NGST Science Steering Committee.

**Peter Sutherland**, a theoretician who works on high-energy astrophysics and computational methods, continued in his position of Dean of Science during the period of this report.

**Douglas Welch** carries out research on variable stars, with much of his work in the analysis of the MACHO database. He completed a three-year term as Chair of the Department of Physics and Astronomy in June 2000.

**Christine Wilson** studies star-forming regions in galaxies through millimeter-wave and radio astronomy. In 2000 she continued in her leadership role as the Canadian Project Scientist for the Atacama millimeter array telescope (ALMA) now in active planning stages. She is also currently Chair of the Advisory Board for the Herzberg Institute of Astrophysics.

### 1.2 Graduate Students and Postdoctoral Fellows

Postdoctoral fellows and research associates in the group during 2000 included J.J. Kavelaars, coming in the fall of 1997 (Ph.D. from Queen's University); Eric Gregersen, arriving in the fall of 1998 (PhD from the University of Texas at Austin); and James Wadsley in the fall of 2000 (PhD from the University of Toronto).

As of September 2000, ten graduate students are enrolled in the group (3 PhD, 7 MSc).

## 2. RESEARCH

### 2.1 Solar System

Kavelaars, working with Gladman, Morbidelli, and Petit (Observatoire de Nice) and Holman (Center for Astrophysics), is conducting an extensive survey of the contents of the 30 to 200 AU region of the solar system (the Edgeworth-Kuiper Belt, or EKB). This region is home to the actively evolving reservoir of material from which short period comets originate. Using deep surveys, obtained at CFHT and VLT, they have confirmed their previous measure of the size distribution of EKB objects. However, their surveys at $20^o$ and $30^o$ indicate that the numbers fall rapidly away from the ecliptic plane and calls into question the current practice of combining all surveys within $5^o$ of the ecliptic. The luminosity function which spans from $R=20$ to $R=26.5$ indicates little deviation from a single power law size distribution. Their off-ecliptic work does hint at a correlation between inclination and size but these results are still very tentative and require further observations to confirm.

Their work has also resulted in the discovery and tracking of the most distant trans-Neptunian object yet discovered (1999 DG8, currently some 65 AU from the Sun) as well as the smallest (1999 DA8). Assuming an albedo of 4-7%, 1999 DA8 is between 10 and 20 km in diameter and represents the first-ever detection of a ''cometary-sized'' body in the EKB. There are now nearly 400 known objects in the EKB, of which Kavelaars *et al.* have discovered roughly 1/4 and made recovery observations of roughly 1/2.

Kavelaars *et al.* have also conducted a near-exhaustive search for irregular satellites of the planets Neptune and Uranus, to a 50% detection limit of magnitude $R\sim 24.3$. Five irregular satellites of Uranus were found, while no new ir-

regulars were found orbiting Neptune. From these observations it appears that, unlike the other gas giants, Neptune was very inefficient at satellite capture and perhaps that its formation had special features. Kavelaars *et al.* have extended their planetary satellite search to Saturn, using the CFHT and ESO 2.2m to detect about two dozen new irregular satellite candidates. At time of writing, four have been confirmed as satellites. The sample is being studied further to determine orbits and eliminate contaminants.

They are also beginning to focus more heavily on acquiring high quality orbits for a large number ($\sim$1000) of bright ($R\sim$23.5) objects in the EKB. Such an orbit database will be crucial to understanding the formation and possible outward migration of Neptune.

Gregersen and Kavelaars are using the Gemini North telescope to begin a study of the dust disk around epsilon Eridani, an analog to the Kuiper belt of our solar system. Since Jupiter-like planets interact strongly with the Kuiper belt, the signature of such a planet would be observable from resonances formed in the disk.

## 2.2 Stellar Populations

### *2.2.1 Old-Halo Stellar Populations*

G.Harris (Waterloo) and W.Harris have used HST imaging with WFPC2 to continue their deep photometric study of the red-giant halo population in the nearest giant elliptical galaxy, NGC 5128. At d = 4 Mpc, this galaxy is near enough that the WFPC2 limiting magnitudes can reach the top three magnitudes in $V$ and $I$ of the Population II giant branch and thus give a direct measure of the metallicity distribution function (MDF) of the outer halo. Results are now complete for three halo fields, located at projected distances of 8, 21, and 31 kpc from the galaxy center. In all three fields, the stars exhibit a very broad MDF with a mean metallicity $\langle$ [/H]$\rangle \simeq -0.4$, asymmetric in form with a sparse low-metallicity tail. Very little 'young' component (age less than about 5 Gyr) is visibly present in the color-magnitude diagram. Simple enrichment models used to interpret the metallicity distribution provide an excellent match if it is assumed that the halo formed through (a) an early ''accreting-box'' stage starting from primordial zero-metallicity material, during which large amounts of gas infall were taking place simultaneously with some star formation; and then (b) a second and more major stage, in which little gas infall took place and the halo evolved nearly as a classic ''closed-box'' system. Only a small fraction of the halo can have accreted from dwarf ellipticals.

### *2.2.2 Variable Stars and MACHO Data*

Welch continued his collaboration with the microlensing survey known as the MACHO Project. This survey finished taking observations at the beginning of January 2000 and is in its final two years of funding.

Welch collaborated with Pierce (Indiana), Stetson (DAO/HIA/NRC), Racine (Montreal), and van den Bergh (DAO/HIA/NRC) to obtain discovery frames for Cepheids in the central Virgo Cluster galaxy NGC 4571, previously searched using the Canada-France- Hawaii Telescope. At time of writing, the final version of the paper is in preparation.

Welch collaborated with Layden (Bowling Green State University) and Webb (UToronto) to survey eight previously unsearched metal-rich galactic globular clusters for RR Lyrae stars. The physical processes which result in the production of metal-rich ([Fe/H] $>-0.8$) RR Lyrae variable stars from an otherwise red horizontal branch population are poorly understood. The results for one cluster, NGC 6441, have been published and the remainder are being analysed.

Welch continued to collaborate with Dr. Geoff Clayton of Louisiana State University on R CrB stars in the MACHO Project data. Work this year has located probable R CrB stars in both the galactic bulge and the SMC.

Welch and his MACHO Project collaborators have discovered a total of three LMC Cepheids which are members of eclipsing binary systems. These are the first such systems to be discovered. More recently, Udalski *et al.* (1999) have reported an additional eclipsing system for which MACHO Project data is also available. These systems are being evaluated at McMaster by Dave Lepischak as part of his M.Sc. thesis. Lepischak has now modelled the lightcurve with a code which incorporates the Cepheid pulsation into the eclipsing binary solution and has determined that two systems (6.6454.5 and 78.6338.24) contain Type 2 Cepheids and one (81.8997.87) contains an intermediate-mass, first-overtone Cepheid.

Welch has continued to work with his MACHO Project colleagues, including affiliates Dr. Christine Clement (Toronto), Dr. Don Kurtz (U Cape Town), and Dr. Geza Kovacs (Konkoly) to explain the long-standing problem of amplitude modulation in RR Lyr stars. This work was published during this reporting period.

In collaboration with Dr. Karen Pollard (Canterbury) and MACHO Project colleagues, Welch established the first persuasive study of the link between the low-mass W Vir and RV Tau pulsators demonstrating the continuity of the P-L relation for these stars and the onset of instability of the lightcurve with increasing period. This work was published during this reporting period.

## 2.3 Globular Star Clusters

### *2.3.1 The Milky Way*

Harris and his students and colleagues have continued a range of studies of globular clusters in the Milky Way and giant E galaxies. Harris, with several colleagues (principally Stetson, Bolte, Hesser, VandenBerg, and Bell) is completing a series of HST-based color-magnitude studies of the Milky Way outermost-halo globular clusters: results for NGC 2419, Eridanus, Palomar 3, and Palomar 4 are now published, and the two remaining outermost-halo clusters (AM-1 and Pal 14) are in progress.

### *2.3.2 Other Giant Galaxies*

Harris, McLaughlin (Berkeley), and G.Harris (Waterloo) are using Cycle 9 HST time with the STIS camera to measure the structural parameters of a large range of *low-mass* globular clusters in M31, and a set of *high-mass* halo clusters

in the giant E galaxy NGC 5128. McLaughlin has found an extremely close correlation between the binding energy $E_b$ and luminosity $L$ of the Milky Way clusters which in detail suggests that the efficiency of star formation within protoclusters increases with cluster mass. By adding similar measurements for the clusters from these other galaxies, they will test out the shape of this correlation there and thus investigate how universal the formation process of old globular clusters was in different types of protogalaxies.

PhD student Vandalfsen, with Harris and Kavelaars, is analyzing the globular cluster populations around two giant edge-on Sa galaxies, NGC 4594 (the Sombrero) and NGC 7814, using wide-field imaging from the Canada-France-Hawaii Telescope. The Sombrero study is particularly comprehensive, taken with the CFH12K array (0.5 degree FOV) and in *BVR*. The metallicity distribution for the clusters in the Sombrero is clearly bimodal, somewhat resembling the Milky Way but with a stronger contribution from the metal-richer population. The specific frequency of the system is $S_N \sim 2$, somewhat lower than previously thought but similar to other giant disk galaxies. Harris and MSc student Okon are using Archival HST/WFPC2 material to analyze the globular cluster populations (specific frequencies and luminosity distributions) around four cD-type galaxies which are at the centers of Abell clusters.

Harris, Kavelaars, and their colleagues published photometric studies of the globular cluster populations around the Coma cluster giants NGC 4874 and IC 4051, using long-exposure HST/WFPC2 images. These galaxies show surprising combinations of characteristics: while the cluster system around the central cD NGC 4874 is quite extended and diffuse, its metallicity distribution is almost entirely metal-*poor*, with $\langle \mathrm{Fe/H} \rangle = -1.5$ and no obvious trace of the metal-rich component that is always expected in such galaxies. Its specific frequency of $S_N = 4$ is also lower than expected (by a factor of 3) for central giants this luminous. Simple numerical models suggest that as much as half of this galaxy might have assembled by accretion of smaller dwarfs in the early Coma cluster. However, the total lack of metal-rich clusters remains a serious puzzle. In IC 4051, we find some opposite puzzles: IC 4051 itself is a ''normal'' gE on the outskirts of the Coma core, probably tidally truncated by repeated high-velocity passages through the central Coma region. But the cluster metallicity distribution is strongly metal-rich at $\langle \mathrm{Fe/H} \rangle \simeq -0.2$ (possibly comprising two narrowly separated modes) with little metal-poor component as is conventionally found in other big ellipticals. Furthermore, though it is not a central giant or cD galaxy, it has a M87-like specific frequency $S_N = 11$ but with the normal Gaussian-like luminosity distribution.

Harris, Kavelaars and their colleagues are continuing similar analyses of the cluster systems in two other Coma giants, NGC 4889 and 4926.

### 2.4 Star Formation in the Milky Way

PhD student Matthews and Wilson are carrying out a large survey of polarized submillimeter emission in nearby molecular clouds. The role of magnetic fields in the formation and evolution of molecular clouds and cores is a key component in current studies of star formation. Earlier observational techniques were limited to only the outer regions of clouds, far removed from the actual locales of star formation. Using the new polarimeter mounted on the Submillimeter Common User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT), they have sampled magnetic field configurations deep within molecular complexes in greater detail and in fainter regions than was previously possible. Regions sampled include OMC-3 in Orion A, a filament in Orion B, Barnard 1 in Perseus, and B2 in rho Ophiuchus. The field configurations, although only two dimensional, support a model for filamentary clouds wrapped with helical magnetic fields. Along most of OMC-3, the field must be toroidally dominated. Matthews, Fiege (CITA), Moriarty-Schieven (JAC) have found the polarization patterns of three regions in Orion B to exhibit signatures of helical fields also, even in regions which are not distinctly filamentary. When combined with future Zeeman measurements, the total field strength and three-dimensional field configuration can be determined.

Mitchell (Saint Mary's), Avery (NRC), Johnstone (Toronto), Wilson, Pudritz, and 8 other collaborators from various Canadian institutions are continuing their large-area survey of the submillimeter continuum emission from the Orion B, Ophiuchus, and Taurus molecular clouds using SCUBA on the JCMT. Johnstone (Toronto), Wilson, Moriarty-Schieven (JAC), Creighton (IPAC), and Gregersen have made a detailed comparison of the characteristics of these large area maps reduced using three different techniques (Emersen, maximum entropy, and iterative reconstruction) to remove the chop function from the data. The results of this comparison is that the iterative reconstruction technique provides the best reconstruction with known noise properties. Johnstone (Toronto), Wilson, Moriarty-Schieven (JAC), Joncas (Laval), Smith (Toronto), Gregersen, and Fich (Waterloo) have analyzed the mass spectrum of the dusty clumps found in the 850 $\mu$m map of the Ophiuchus molecular cloud. The clumps were identified using the automatic identification algorith ''ClumpFind'' and have masses ranging from 0.02 to 6 $M_\odot$. The mass function shows a broken power law, although incompleteness may affect the slope at the low-mass end.

Gregersen has begun a collaboration with Dr. Gerald Moriarty-Schieven (JAC) to search for protostellar collapse in the starless cores discovered in the Canadian SCUBA consortium maps of the Ophiuchus star-forming complex. This survey will be the first search for collapse in a complete sample of such starless cores. Gregersen has also been working with Pudritz and Wilson on testing theories of a column density threshold as the necessary condition for star formation. Submillimeter continuum observations have been done on seven cores and further molecular line and continuum observations are planned to find if there is a link between infall signatures and column density. Gregersen has also begun a collaboration with Basu (Western Ontario), Ciolek (Rensselaer) and Choi (ASIAA) on testing ambipolar diffusion models of a starless core. The loss of magnetic support through ambipolar diffusion is at the heart of the standard theory of low-mass star formation, but only recently have

specific models appeared that can be observationally tested.

### 2.5 Interstellar Medium in Galaxies

PhD student Petitpas and Wilson have been carrying out a detailed survey of molecular gas in double-barred spiral galaxies. Recent near-infrared surveys show that many barred galaxies contain isophote twists which are thought to be the signature of a 'bar within a bar'. They have obtained high resolution observations from the Caltech Millimeter Array for a number of these galaxies in CO J=1-0 and find that double bars are not always present in the molecular gas in these galaxies. In fact, the galaxies exhibit a variety of nuclear morphologies when viewed in CO, including rings, spirals and in some cases, bars. This result seems to suggest that the molecular gas is responding differently to the large scale galactic potential in each of these galaxies. Analysis of preliminary multi-line data suggests that the gas is noticably warmer in galaxies that contain nuclear CO bars than in the galaxies without.

Wilson, Scoville (Caltech), Madden (Saclay) and Charmandaris (Paris/Cornell) are carrying out a detailed study of the molecular interstellar medium in the Antennae system (NGC 4038/39) using the Caltech Millimeter Array. CO maps with a spatial resolution of $\sim$500 pc reveal numerous massive gas complexes, with a very high concentration towards the region in the Antennae where the two disks appear to overlap. The data are able to probe the mass spectrum of these molecular complexes over nearly two decades in mass. The ultimate goal is to provide constraints on how the many massive star clusters in the Antennae system might have formed. Wilson and Spekkens (Cornell) are carrying out a similar study of the isolated galaxy NGC 5248, which also contains massive star clusters, to compare the properties of the gas complexes in interacting versus isolated galaxies.

Wilson, Madden (Saclay) and Jones (IAS) have begun a program to study the dust properties of low metallicity dwarf galaxies using SCUBA on the JCMT. Initial observations of NGC 1569 and IIZw40 have revealed 850 $\mu$m fluxes that are substantially higher than would be expected from a modified black-body fit to the IRAS data points. This bright emission at sub-millimeter wavelengths may indicate a significant population of very cold dust grains and has important implications for the gas-to-dust ratio in low-metallicity systems. Wilson, Petitpas, Madden (Saclay), and Taylor (FCRAO) have begun a program to obtain large-area sub-millimeter maps of the local group dwarf galaxy IC10. These data will provide a higher-resolution view of a low metallicity galaxy and may provide constraints on the suggestion that there are large amounts of $H_2$ that are not traced by CO emission in this galaxy.

### 2.6 Astrophysics of Star Formation

Pudritz and his students and colleagues have focused their research on star formation in the local interstellar medium, as well as in the context of galaxy formation. In the galactic context, new theoretical models for for filamentary molecular clouds and their star-forming prolate cores have been completed, and predictions for submillimetre polarimetry observations of such systems computed. New models and simulations of the formation of star clusters within cores are underway, and the 3-D simulation of bipolar outflows and jets from accretion disks is nearly completed. On cosmological scales, numerical simulations of the formation of self-gravitating supergiant clouds within the dark matter potential wells produced in hierarchical cosmological models of galaxy formation have now been demonstrated.

#### *2.6.1 Accretion Disks:*

Pudritz is constructing a theoretical model for the structure of magnetized accretion disks and their interaction with the magnetospheres of young stellar objects. A central feature of this model is that the outflows from disks can carry off most of the gravitational binding energy released through disk accretion, implying that their radial inflow velocities are a considerable fraction of the Kepler speed.

Pudritz and Pelletier are constructing a general model of the heating mechanism of magnetized accretion disks. The only known mechanism for driving turbulence in accretion disks is the Balbus-Hawley instability. The manner in which such turbulence damps to heat disks has always been an important but unsolved problem. They show that the mechanism of phase mixing of Alfvén waves as they propagate vertically through an accretion disk, leads to strong wave damping. Early calculations show that the gravitational potential energy that is locked up in the wave flux is deposited into the upper layers of the disk where it heats the gas.

With Wolfgang Dobler (Newcastle), Pudritz is working on the simulation of 3-D magnetized accretion disks. The aim of these global numerical simulations is to demonstrate both the existence of Balbus-Hawley turbulence within the disks, as well as the conditions necessary for the launch of a disk wind. These are among the first global simulations of such processes being attempted.

#### *2.6.2 Jets:*

Ouyed and Pudritz, in a series of 1997 papers, were able to simulate the acceleration and collimate of jets from the surfaces of magnetized accretion disks. The computations were done in 2-D and used Stone and Norman's ZEUS 2-D code.

Ouyed, Clarke, and Pudritz (2000, in preparation) are writing up the results of ZEUS 3-D simulations of jets from accretion disks. These simulations are carried out with the same physical set-up as in the Ouyed and Pudritz work. The main physical concern in 2-D models for jets is that they are prone to highly destructive, kink-type, non-axisymmetric instabilities in 3-D. This recent work demonstrates that jets manage to stabilize themselves against threatened instabilities of this kind.

Pudritz, Rogers, and Ouyed (2000, in preparation) have simulated generalized 2-D, disk wind models in which any desired power-law distribution of magnetic field on the disk can be studied, including the Blandford &Payne and Pelletier & Pudritz magnetic configurations. The results of the simulations show that the launching of jets is very robust, and is largely independent of the details of the magnetic structure of the disks.

Königl and Pudritz (2000) reviewed the observations, theory, and numerical simulation of jets in protostellar systems which has appeared in Protostars and Planets IV. Pudritz (2000) completed a theoretical study of mechanisms of jet formation.

### *2.6.3 Molecular Clouds and Their Cores:*

Fiege (CITA) and Pudritz completed a new theory for the structure and fragmentation of filamentary molecular clouds. Recent observations of filamentary molecular clouds have shown that their radial density profiles decline as $r^{-2}$, rather than the steep $r^{-4}$ dependence that is expected from self-gravitating isothermal filaments (Ostriker, 1964). In addition, a wealth of new observations of the polarization of submm emission from molecular clouds has become available from JCMT observations.

Fiege and Pudritz have created general axisymmetric models of magnetized filaments that include both poloidal and toroidal magnetic fields (i.e., a helical field) as well as external pressure on the filament. Their model produces density profiles that are in good agreement with the data. They show that such filaments undergo fragmentation but at rates and over length scales that are different than in models with purely poloidal field. It was shown that a relatively small contribution of toroidal field actually helps to stabilize the cloud to fragmentation.

Fiege and Pudritz have also completed a new model for the observed elongated structure of star-forming cores in molecular clouds. It has been known for many years that star forming clumps in molecular clouds are prolate in shape. This is difficult to understand for models of filaments that invoke purely poloidal magnetic field - fragments in such structures rapidly collapse along field lines to produce oblate pancakes, not prolate bodies. Fiege and Pudritz discovered new prolate MHD clump equilibria that arise as the nonlinear end-state of the fragmentation of helically magnetized filaments.

Fiege and Pudritz completed a new theory for the structure and fragmentation of filamentary molecular clouds. Recent observations of filamentary molecular clouds have shown that their radial density profiles decline as $r^{-2}$, rather than the steep $r^{-4}$ dependence that is expected from self-gravitating isothermal filaments (Ostriker, 1964). In addition, a wealth of new observations of the polarization of submm emission from molecular clouds has become available from JCMT observations.

Fiege and Pudritz have now also completed the computation of the submillimetre polarimetric maps that would be produced by their filamentary cloud models. A major prediction of their theoretical models is that depending on the strength of the toroidal relative to the poloidal field in the filament, polarization vectors lie along, or perpendicular to the filaments. Detailed comparisons of their filament and core models are currently being made by others in the Canadian JCMT SCUBA consortium maps of nearby molecular clouds. Pudritz is one of the original theory members of this large Canadian collaboration which has won a considerable amount of SCUBA time over the last two years to systematically study star formation in the Orion, $\rho$ Oph, and Taurus molecular clouds.

Pudritz and summer student Daniel Parker ran hydrodynamic, 3-D simulations of self-gravitating molecular cloud clumps using Couchmans HYDRA code. By imposing power-law spectrum of (Gaussian) density fluctuations, they were able show that cores and filaments evolve. Cores, though, do not always result from the fragmentation of the filaments. They also measured the radial density profiles of the filaments and found them to be too steep (approximating Ostriker profiles) to explain the observations. This seems to suggest that filaments need to be magnetized (as in the Fiege and Pudritz models).

Basu (Western Ontario) and Pudritz are completing a new theoretical model for the formation of star clusters which is based on the evolution of a Gaussian field of column density fluctuations above a critical threshold value. The observations of molecular cloud clumps show that those of sufficiently high column density (above $10^{22}$ particles per cubic cm), undergo star formation, while lower column density regions are starless. They are able to demonstrate that both the supporting pressure of both an ordered magnetic field, as well as MHD turbulence, damps out at these high column densities.

With David Clarke (St. Mary's), Pudritz is working on the development of a new adaptively refined, mesh code for doing magnetized collapse problems in star formation theory. While hydrodynamic AMR codes have now arrived and have made a large impact on the simulation of star formation, AMR MHD codes are now in the process of development in several groups around the world. Such a code, when completed, will be employed by M.Sc. students David Tilley and Michael Reid in Pudritz's group in studying the formation of filamentary clouds, and the collapse of magnetized cores within them.

## 2.7 Cosmology

Weil (CUNY) and Pudritz have submitted their first paper on the cosmological evolution of supergiant star forming clouds during galaxy assembly. The idea that globular cluster formation occurs within very massive $10^8$ solar mass clouds was laid out by Harris and Pudritz (1994) and McLaughlin and Pudritz (1996). The extension of this work to a hierarchical merging picture of galaxy formation has now been accomplished. Weil and Pudritz employ a tree-SPH code in order to investigate the growth of small dwarf-galaxy mass dark matter wells during heirarchical galaxy formation. Our simulations resolve the growth of self-gravitating clouds of a million solar masses and more, and compare the properties of these structures with those predicted by the simple analytic models described above. They find that such massive clouds do indeed form, and that they have the mass spectrum of GMCs as predicted from the globular cluster luminosity function.

Couchman carried out several, primarily numerical, investigations of the formation of cosmic structure. The overarching goal of the research is to develop realistic models of galaxy formation using high performance computers in conjunction with efficient numerical algorithms.

With the Virgo consortium (a Durham, UK-based supercomputer collaboration), Couchman was involved with a series of very high resolution hydrodynamic simulations of the distribution of galaxies in a cubic region 80Mpc on a side. This was the first hydrodynamic simulation to identify a significant number of galaxies at such high resolution in a cosmological volume. A number of other projects are underway as part of the Virgo collaboration including an investigation of the radial density profiles of haloes forming in Cold Dark Matter (CDM) models, to determine if the apparently universal profiles found in dark-matter-only simulations by many workers can be affected by the presence of cooling baryons; as well as a series of large baryonic simulations designed to produce a large catalogue of simulated X-ray clusters.

Couchman, Scoccimarro and Peebles (Princeton) are continuing and investigation of the renormalization idea of Peebles to include higher order perturbative corrections at the renormalization step. It is hoped that this will provide a robust prediction for statistics such as the two- and three-point correlation functions in a stable clustering hierarchy. An important aim of this study is to set constraints on the limits of conventional simulations. The expense of the renormalization method as well as its restriction to power-law initial spectra prevents it from gaining widespread use as a primary simulation tool, but it provides a vital baseline against which to judge the range of applicability of conventional techniques.

Thacker (Berkeley) and Couchman completed the highest resolution simulation of the formation of an individual disc galaxy to date. The aim was to model the formation of a disc in a hierarchical CDM cosmology including the proper cosmological context and internal feedback on the galactic ISM from massive stars. We have shown that even with reasonable feedback models, overcooling of dense gas at early epochs remains a problems in these models. Although very high levels of feedback can improve the situation and help to increase the specific angular momentum of the disc towards that observed in galaxies, it is unclear at this stage if this will provide enough freedom to permit CDM-like models to provide a useful formation model for observed galaxies without the addition of other, as yet unrecognised, physics. This area remains a central focus of research.

With Fuller (Ph.D student, Western Ontario), Couchman is continuing an investigation of the formation of the first generation of stars in the high redshift universe. In hierarchical models, small bound haloes form first. The first low-mass haloes have a virial temperature below $10^4$ K and the baryons will cool as a result of the formation of a fractional abundance ($<10^{-}3$) of molecular hydrogen. The appropriate chemical reactions responsible for the formation and destruction of molecular hydrogen have been incorporated in the the hydrodynamic code ''Hydra.'' We have found that there is a sharp, redshift-dependent, mass threshold above which cooling becomes so efficient that collapse occurs on the free-fall time of the dark matter halo. These simulations are now being scaled up so that we can investigate the impact of feedback of the first objects on the pre-galactic medium: this is an essential prerequisite for setting the initial conditions for galaxy formation.

An important component of the numerical investigation of structure formation is the development and testing of efficient algorithms. With Tittley (Maryland, Baltimore County), Couchman has completed a study of drag in the commonly used Smoothed Particle Hydrodynamic (SPH) technique. It is widely believed that infalling satellites in numerical simulations will suffer anomalously large amounts of drag and hence merge more rapidly than realistic. We have quantified this effect, as well as comparing the relative magnitude of the effect in the various popular ways if implementing SPH in cosmological codes. Tittley and Couchman have also investigated claims that it is necessary to resolve the Jeans mass in cosmological simulations in order to achieve convergence with increasing simulation resolution. We have shown that this is not the case in hierarchical simulations provided that the virialised object under consideration have undergone several mergers. Both of these studies have been submitted for publication.

With Thomas (Sussex) and Pearce (Durham), Couchman is preparing a completely rewritten version of the cosmological simulation code Hydra which it is expected will be publicly released in 2000. Following initial public release in 1996 this cosmological particle code has become widely used worldwide. The new version is more robust and offers a factor of two increase in performance on given hardware whilst tightly controlling memory use. In concert with the above effort, the Virgo consortium and the Edinburgh Parallel Computing Centre (EPCC), are working to provide a fully portable parallel (MPI) implementation of Hydra which will run on platforms from the massively parallel Cray T3E to inexpensive Beowulf clusters. This effort which has consumed over three years of effort is expected to be largely completed within the next 8 months.

## PUBLICATIONS

The publication list includes all refereed papers appearing in print from January 2000 through September 2000 in which McMaster personnel were authors or co-authors.

Alcock, C., Welch, D. L. *et al.* 2000, ''The MACHO Project Sample of Galactic Bulge High-Amplitude $\delta$ Scuti Stars: Pulsation Behavior and Stellar Properties,'' ApJ, 536, 798

Alcock, C., Welch, D. L. *et al.* 2000, ''The MACHO Project 9 Million Star Color-Magnitude Diagram of the Large Magellanic Cloud,'' AJ, 119, 2194

Alcock, C., Welch, D. L. *et al.* 2000, ''The MACHO Project: Microlensing Depth toward the Galactic Bulge from Difference Image Analysis,'' ApJ, 541, 734

Alcock, C., Welch, D. L. *et al.* 2000, ''The MACHO Project: Microlensing Results from 5.7 Years of Large Magellanic Cloud,'' ApJ, 542, 281

Alcock, C., Welch, D. L. *et al.* 2000, ''The MACHO Project: Large Magellanic Cloud Variable-Star Inventory. IX. Frequency Analysis of the First-Overtone RR Lyrae Stars and the Indications for Nonradial Pulsations,'' ApJ, 542, 257

Bolatto, A. D., Jackson, J. M., Wilson, C. D., & Moriarty-Schieven, G. 2000, ''Submillimeter Observations of IC 10: The Dust Properties and Neutral Carbon Content of a Low-Metallicity Starburst,'' ApJ, 532, 909

Colberg, J. M., White, S. D. M., MacFarland, T. J., Jenkins, A., Pearce, F. R., Frenk, C. S., Thomas, P. A., & Couchman, H. M. P. 2000, ''Peculiar Velocities of Galaxy Clusters,'' MNRAS, 313, 229

Fiege, J. D., & Pudritz, R. E. 2000c, ''Helical Fields and Filamentary Molecular Clouds. I,'' MNRAS, 311, 85

Fiege, J. D., & Pudritz, R. E. 2000b, ''Helical Fields and Filamentary Molecular Clouds. II,'' MNRAS, 311, 105

Fiege, J. D., & Pudritz, R. E. 2000c, ''Prolate Cores in Filamentary Molecular Clouds,'' ApJ, 534, 291

Gregersen, E. M., & Evans, N. J. II, ''How to Identify Pre-Protostellar Cores,'' ApJ, 538, 260

Gregersen, E. M., Evans, N. J. II,, Mardones, D., & Myers, P. C. 2000, ''Does Infall End Before the Class I Stage?,'' ApJ, 533, 440

Harris, W. E., Kavelaars, J. J., Hanes, D. A., Hesser, J. E., & Pritchet, C. J. 2000, ''The Globular Cluster Systems in the Coma Ellipticals. II: Metallicity Distribution and Radial Structure in NGC 4874, and Implications for Galaxy Formation,'' ApJ, 533, 137-148

Kavelaars, J. J., Harris, W. E., Hanes, D. A., Hesser, J. E., & Pritchet, C. J. 2000, ''The Globular Cluster Systems in the Coma Ellipticals. I: The Luminosity Function in NGC 4874, and Implications for Hubble's Constant,'' ApJ, 533, 125-136

Kay, S. T., Pearce, F. R., Jenkins, A., Frenck, C. S., White, S. D. M., Thomas, P. A., & Couchman, H. M. P. 2000, ''Parameter Tests Within Cosmological Simulations of Galaxy Formation,'' MNRAS, 316, 374

Matthews, B. C., & Wilson, C. D. 2000, ''Magnetic Fields in Star-Forming Molecular Clouds. I. The First Polarimetry of OMC-3 in Orion A,'' ApJ, 531, 868

Pearce, F. R., Thomas, P. A., Couchman, H. M. P., & Edge, A. C. 2000, ''The Effect of Radiative Cooling on the X-ray Properties of Galaxy Clusters,'' MNRAS, 317, 1029

Petitpas, G. R., & Wilson, C. D. 2000, ''Temperature and Density Gradients Across the Nucleus of M82,'' ApJ, 538, L117

Pudritz, R. E. 2000, Phil. Trans. R. Soc. Lond. A, 358, 741

Taylor, C. L., & Wilson, C. D. 2000, ''The Spatial Distribution of Atomic Carbon Emission in the Giant Molecular Cloud NGC 604-2,'' ApJ, 538, 134

Tittley, E. R., & Couchman, H. M. P. 2000, ''Resolving the Jeans Mass in Hydrodynamic Simulations of Hierarchical Clustering,'' ApJ, 539, 124

Tittley, E. R., & Couchman, H. M. P. 2000, ''Hierarchical Clustering and the Baryon Distribution in Galaxy Clusters,'' MNRAS, 315, 834

Woodworth, S. C., & Harris, W. E. 2000, ''The Globular Clusters in the Coma Ellipticals. III: The Unique Case of IC 4051,'' AJ, 119, 2699

William E. Harris