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The following report summarizes the activities of the Astronomy and Astrophysics Group of the Department over the period September 1997 through December 1999. Our last report appeared in 1998 in Bull. AAS Volume 30. Current information about our people and facilities 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** joined us in the fall of 1999, coming from the University of Western Ontario. His research area is in theoretical cosmology and the numerical simulation of galaxy formation through high performance computing. **William Harris** carries out observational studies of globular clusters and the distance scale. In 1998 he gave series of invited lectures at the Saas-Fee Advanced School in Astronomy and Astrophysics, and at the Canary Islands Winter School in Astrophysics. He joined the Board of Directors of the Canada-France-Hawaii Telescope in 1998, and was a member of the 7-person Long Range Planning Panel for Canadian Astronomy during 1998/2000. Other activities included chairing one of the time allocation panels for Cycle 8 of HST in 1998, and chairing the 1998 Peer Review Panel for the Herzberg Institute of Astrophysics. He continues as a member of the Canadian Gemini Steering Committee. **Ralph Pudritz** is a theoretical astrophysicist who carries out a wide range of programs in the physics of star formation and galaxy formation. During 1998/2000 he chaired the NRC/NSERC/CASCA Long Range Planning Panel for Canadian Astronomy, the final report for which was completed in October 1999. He is now helping to design and drive an outreach campaign to disseminate the results of the report, "*The Origins of Structure in the Universe: Canadian Astronomy and Astrophysics in the 21st Century*" to the funding agencies, government, and media. Pudritz also continued on the Canadian Time Allocation Group (CTAG) for the JCMT until the end of 1999. He continues as a member of CITA Council till June 2000, and as a member of the Canadian Gemini Steering Committee, as well as 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 continued as Chair of the Department of Physics and Astronomy during the period of this report. **Christine Wilson** studies star-forming regions in galaxies through millimeter-wave and radio astronomy. In 1999 she

took up the Canadian Project Scientist position for the multinational millimeter array telescope (ALMA) now in its planning stages. She is also currently Chair of the Advisory Board for the Herzberg Institute of Astrophysics. In 1998 she finished a 3-year term as Councillor on the Board of the Canadian Astronomical Society. During the 1998/99 academic year she spent research leave at Caltech.

1.2 Graduate Students and Postdoctoral Fellows

Postdoctoral fellows joining the group included J. J. Kavelaars, coming in the fall of 1997 (Ph.D. from Queen's University); Eric Gregersen, in the fall of 1998 (PhD from the University of Texas at Austin); and Melinda Weil, from August 1998 to September 1999 (PhD from UC Santa Cruz). Dr. Weil took a faculty position at CUNY in the fall of 1999. Kavelaars changed to the position of Research Associate within our group in 1999 and did part-time graduate instruction as well.

As of January 2000, nine graduate students are enrolled in the group (4 PhD, 5 MSc). Students who graduated in the past two years include Jason Feige, who completed his PhD work with Pudritz in 1999 and took a postdoctoral fellowship at CITA; Sean Woodworth, who completed an MSc with Harris in 1998 and has continued to PhD studies in Engineering Physics; and Tracy Webb, who completed an MSc in 1998 with Welch and has moved to the University of Toronto for PhD work in astronomy.

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. Their work is currently focusing on deep and wide field surveys of the EKB population in order to constrain the size distribution of planetesimals in this region.

Their deep pencil-beam observations, obtained with the CFHT and VLT facilities, indicate that the density of small bodies in the EKB is about twice that expected from a uniform power-law distribution extrapolated from previous surveys of the bright end of the distribution function. This may indicate that the accretion phase of this region of the solar system was truncated before an equilibrium size distribution could be established. Such a truncation could be caused by the scattering of large ($\sim 1 - 5M_{\oplus}$) planetary embryos into the belt region. Notably, their work has 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.

Kavelaars *et al.* have also conducted a near-exhaustive search for irregular satellites of the planets Neptune and Uranus, covering 85% of the Hill spheres to a 50% detection limit of magnitude $R \sim 24.3$. Their search resulted in the discovery of five irregular satellites of Uranus while no new irregulars 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, Holman, and Gladman have acquired deep survey fields 20° and 30° above the ecliptic using CFHT and the KPNO 4m. They are currently completing the analysis of their deep off-ecliptic survey which will be the first to probe the thickness of the EKB region directly, an important parameter in constraining the late stage evolution of this region of the solar system. They are also beginning to focus more heavily on acquiring high quality orbits for a large number (~ 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.

2.2 Stellar Populations

2.2.1 Old-Halo Stellar Populations

G. Harris (Waterloo) and W. Harris used the WFPC2 camera on HST to carry out a 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. Their results for a field 20 kpc from the galaxy center show that the stars have a very broad MDF with a mean $\langle [\text{Fe}/\text{H}] \rangle \approx -0.7$, probably bimodal in form and extending above solar metallicity. The bulk of this galaxy could have formed as a result of two major bursts of star formation and metal enrichment at quite early times; very little ‘young’ component is visibly present.

Harris and Harris are extending this work to the analysis of two additional NGC 5128 halo fields, a still more remote one at 40 kpc and an inner one at 10 kpc, both from HST Cycle 8 photometry. With this material they intend to begin studying the way the MDF changes with radius within the halo of this uniquely valuable galaxy. Harris, Durrell (UBC), Pierce (Indiana), and Secker (CCRS/Ottawa) also used WFPC2/HST to resolve the brightest red giant stars in a Virgo cluster dwarf elliptical and thus to use the red-giant tip luminosity for a direct distance calibration to Virgo. The result of $(m - M)_0 = 31.0$ agrees closely with the mean Cepheid and planetary-nebula calibrations and confirms the effectiveness of the TRGB technique out to 15 – 20 Mpc distances.

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.

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. A sequence of appropriately spaced frames was finally completed in July 1999 and has been analysed for Cepheids. A preliminary distance has been determined for this important galaxy.

Rorabeck completed an update of his M.Sc. thesis with Welch where he undertook the observational characterization of second-overtone Cepheid pulsation using double-mode (first/second-overtone) pulsators in the LMC and SMC using MACHO Project photometry.

Welch continued to collaborate with Dr. Geoff Clayton of Louisiana State University on R CrB stars in the MACHO Project data. This has produced the first modern study of these evolved, hydrogen-deficient pulsators. Our work has now revealed that the luminosities of these stars are typically one magnitude fainter than had been assumed from previous work on the small number of candidates towards the LMC. A dozen of these stars have now been spectroscopically confirmed.

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 are also available. These systems are being evaluated by Dave Lepschak as part of his M.Sc. thesis.

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. Samples of many thousand RRab and RRC stars have now been examined and have revealed both amplitude and phase modulation in both pulsation modes.

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.

Webb completed an M.Sc. thesis with Welch (in collaboration with Wilson) to determine the effect of metallicity on the absolute magnitudes of M31 Cepheids in the near-infrared using CFHT data. The effects of errors in reddening and differential reddening are dramatically reduced by this technique. The measured gradient and uncertainty are consistent with zero, in agreement with previous optical work.

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) completed a series of HST-based color-magnitude studies of the Milky Way outermost-halo globular clusters NGC 2419, Eridanus, Palomar 3, and Palomar 4. Their deep WFPC2 (V,I) data delineated 3 magnitudes of the main sequence in these clusters and permitted careful matching to theoretical isochrones for age and metallicity determination. The published results show that NGC 2419 is basically a clone of the nearby ‘‘standard’’ low-metallicity cluster M92 (and thus that star formation in the outer halo began virtually as early as in the inner halo). However, the intermediate-metallicity objects Eridanus, Pal 3, and Pal 4, all of which display the second-parameter red-HB anomaly to varying degrees, appear to be 1 to 2 Gyr younger than the template comparison clusters like M3 and M5. This work is now continuing to new data for Palomar 14 and AM-1, after which the HST/WFPC2 survey of the outermost-halo clusters will be complete.

2.3.2 Other Giant Galaxies

Harris, McLaughlin (Berkeley), and G.Harris (Waterloo) will be using Cycle 9 HST time with the STIS camera to measure the structural parameters of a large range of low-luminosity globular clusters in M31 and a similarly large range of 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 . Preliminary results indicate a clearly bimodal metallicity distribution for the clusters and a specific frequency $S_N \sim 2$, somewhat lower than previously thought but similar to other giant disk galaxies.

Harris, Kavelaars, Hanes (Queen’s), Pritchett (Victoria), and Hesser (HIA/NRC) have completed a photometric study of the globular cluster population around the Coma cluster central cD galaxy NGC 4874, using long-exposure HST images from WFPC2. Not surprisingly, they find that the cluster system around this very diffuse and luminous galaxy is similarly extended spatially. Surprisingly for any E galaxy this luminous, however, the cluster metallicity distribution is almost entirely metal-poor, with $\langle \text{Fe}/\text{H} \rangle = -1.5$ and no obvious trace of the metal-rich component that is always expected in such galaxies. The 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. How-

ever, the total lack of metal-rich clusters remains a serious puzzle.

Similar work is continuing for two other Coma giants, NGC 4889 and 4926 (from HST Cycle 8) is continuing. The luminosity functions for the globular clusters in these four Coma ellipticals (including IC 4051 described below) will eventually be used for a strong distance determination to Coma and thus a new calibration of the Hubble constant. A preliminary analysis using the GCLF turnovers in IC 4051, NGC 4874, and a handful of nearer giant ellipticals, gives $H_0 = 69 \pm 9$ km/s/Mpc on a distance scale where Virgo is at $(m - M)_0 = 31.0$. The future addition of more giant E galaxies at Coma-like distances has the promise to reduce the internal uncertainty in H_0 by almost a factor of two.

Harris, with MSc students Okon and Woodworth, has used the HST Archive to analyze the cluster systems around several giant ellipticals at large distances. The first of these, IC 4051 in Coma, proves to be a strikingly unusual system: 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. The metallicity distribution of its globular clusters is strongly metal-rich at $\langle \text{Fe}/\text{H} \rangle \approx -0.2$ (possibly comprising two narrowly separated modes) with no detectable metal-poor component. 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. This galaxy, and NGC 4874 described above, provide intriguing challenges to the conventional pictures of globular cluster system formation.

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, will provide tests and constraints on models of filamentary clouds requiring magnetic field support against gravity, and when combined with future Zeeman measurements, can yield the field strength as well as three-dimensional configuration.

Wilson, Howe (FCRAO) and graduate student Balogh (Victoria) completed a large-area survey of the molecular cloud M17 in the $J=2-1$ and $J=3-2$ emission lines of ^{12}CO and ^{13}CO . They observe a correlation between the $^{12}\text{CO}/^{13}\text{CO}$ line ratios and the ^{13}CO integrated intensity, which is likely due to variations in the column density from one position to another within M17. Comparison of these data with data for cloud cores and for external galaxies reveals a clear

trend of increasing $^{12}\text{CO}/^{13}\text{CO}$ line ratios as one moves to larger scales. This trend is present for at least the three lowest rotational transitions. The most likely explanation of the high line ratios for normal galaxies is a significant contribution to the CO emission by low column density material, such as diffuse molecular clouds or the outer envelopes of giant molecular clouds.

In 1998, Mitchell (Saint Mary's), Avery (NRC), Johnstone (Toronto), Wilson, Pudritz, and 5 other collaborators from various Canadian institutions began a large project to obtain large-area maps of the submillimeter continuum emission from the Orion B, Ophiuchus, and Taurus molecular clouds using SCUBA on the JCMT. Data have been obtained to date for the northern half of Orion B and for most of Ophiuchus. An initial analysis of only a portion of the Ophiuchus data revealed a wide variety of large-scale features that were previously unknown. These include linear features that may correspond to the walls of an outflow cavity or a photon-dominated region, new, compact submillimeter source, and two arcs of emission that may be associated with the VLA 1623 outflow. Further analysis of the Ophiuchus and Orion B data sets has focused on the clump mass spectrum and a comparison of the clump masses determined independently from molecular line data and the continuum data. Polarization maps have also been obtained for some of the brighter regions in Orion B.

Gregersen is collaborating with Shirley and Evans (Texas) and Rawlings (University College) on a program of mapping the continuum emission from 21 of the youngest stellar objects, from starless cores to Class I sources, with JCMT/SCUBA to test how protostellar collapse changes the matter distribution. This collaboration has shown that many of these sources have a multiplicity that would lead to an erroneous interpretation of their spectral energy distribution. Gregersen has also begun observations with Evans and Shirley (Texas), Mardones (Chile), Myers (Harvard) and Wilson of later Class I sources in Taurus with the JCMT in the HCO^+ $J=3-2$ line, a line that easily shows the protostellar collapse signature, to see when protostellar collapse ends and how inflow motions change with time. This collaboration has also done similar work in Chamaeleon and Corona Australis with SEST. Previous observations of Class I sources showed asymmetries indicative of collapse in several sources.

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. They are also undertaking a multi-line CO study with the JCMT to

obtain a complete set of molecular gas data which will allow them to determine the physical conditions of the molecular gas in this sample of double barred galaxies.

Wilson, Scoville (Caltech), Madden (Saclay) and Charmandaris (Paris/Cornell) have been carrying out a detailed study of the molecular interstellar medium in the Antennae system (NGC 4038/39) using the Caltech Millimeter Array. The Antennae are the closest example of a merger of two nearby spiral galaxies and thus provide an unique opportunity to study the internal workings of star formation in a galaxy merger. Key results from this work to date include the identification of extremely large ($> 10^8 M_{\odot}$) gas complexes that appear to be gravitationally bound, and evidence for cloud-cloud collisions which may be enhancing both the star formation rate and the mid-infrared emission from the region between the two galaxy nuclei.

Graduate student Giannakopoulou-Creighton, Fich (Waterloo), and Wilson completed a study of the molecular interstellar medium in the giant HII regions of the nearby spiral galaxy M101. This work was Creighton's Ph.D. thesis at Waterloo. One interesting result from this study is that the molecular clouds in one of the giant HII regions appear much brighter in CO than would be expected from their virial masses, which suggests that heating of the clouds by the massive star formation is influencing the CO emission from the clouds.

Wilson has been continuing to study the atomic carbon emission from Local Group galaxies. Taylor (Bochum/FCRAO) and Wilson have made a small map of the atomic carbon emission in the giant HII region NGC 604 in the spiral galaxy M33. This map reveals evidence for an offset between the CI and the CO emission, with the CI offset towards the massive stars. This result strongly suggests that the dominant source of CI emission in this region is from UV-photodissociation. Bolatto, Jackson (Boston), Wilson, and Moriarty-Schieven (JAC) have studied the atomic carbon and submillimeter continuum emission from several regions in the irregular galaxy IC 10. Comparison of the CI data with results from the LMC suggests that the CI/CO ratio in molecular clouds is not a simple function of the metallicity of the host galaxy, but that other factors must also play a role.

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. The scope of the research on local star formation encompasses the development of new models for filamentary molecular clouds and star-forming prolate cores and clumps within them, the physics of star cluster formation, and the simulation of bipolar outflows and jets. These ideas are being applied to the study of the formation of self-gravitating supergiant clouds within the dark matter potential wells produced in hierarchical cosmological models of galaxy formation.

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. We are able to 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. This approach is very general and uses methods well known to plasma physicists and solar astrophysicists.

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 and Pudritz have now extended these simulations to investigate the effect of mass loading on the physics of the jet. Their earlier work suggested that if the wind mass loss rate per unit magnetic flux threading the disk is lowered, then the jets manifest episodic time behaviour. The results of the 1999 study confirmed this with a large number of simulations.

Jet research in Pudritz's group has branched into two new directions. Pudritz, Ouyed, and Rogers have created 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. In a separate line of work, Ouyed, Clarke, and Pudritz have nearly completed their study of the acceleration and stability of disk winds in 3-D. As is well known, magnetic systems such as jets are prone to kink-type instabilities in 3-D which could easily destroy jets. Our results suggest that jets are in fact stable in 3-D, a result that is of great significance to our overall understanding of why jets are so ubiquitous in nature.

Königl and Pudritz (2000, in press) completed an exhaustive review of the observations, theory, and numerical simulation of jets in protostellar systems for the book, *Protostars and Planets IV*.

2.6.3 Molecular Clouds and Their Cores

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 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.

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 non-linear end-state of the fragmentation of helically magnetized filaments.

They have now also computed the submillimetre polarimetric maps that would be produced by their filamentary cloud models and have shown 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 will be made using 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, ρ Oph, and Taurus molecular clouds.

2.7 Cosmology

Pudritz and Weil (now at CUNY) are generalizing the ideas of globular cluster formation laid out in the Harris and Pudritz (1994) and McLaughlin and Pudritz (1996) papers to the case of hierarchical galaxy formation and its attendant star formation. These earlier papers proposed that globular clusters formed in the massive cores of supergiant molecular clouds (of mass typically $10^8 M_{\odot}$). This new work investigates how globular cluster systems around galaxies were formed in a hierarchical merging picture of galaxy formation. They employ a tree-SPH code in order to investigate the growth of small dwarf-galaxy mass dark matter wells during hierarchical 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. Dense cores of the required mass do indeed seem to form within larger gas structures.

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 super-computer collaboration), Couchman was involved with a se-

ries 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, Scoccamarro and Peebles (Princeton) have extended 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, a Ph.D. student supervised jointly by Couchman and Page (Alberta) gained his degree from the University of Alberta in August and is now at Berkeley. Thacker 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 problem 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 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 compared the relative magnitude of the effect in the various popular ways of 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 has 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 the inexpensive Beowulf clusters. The team is working at present to incorporate adaptive refined grids (required where particles cluster in the simulations in order to maintain efficiency) into the previously developed unadaptive code.

PUBLICATIONS

The publication list includes all papers appearing in print from September 1997 through December 1999 in which McMaster personnel were authors or co-authors. This range of dates covers the period since our last report.

- C. Alcock, D. L. Welch *et al.* 1997, "The MACHO Project Large Magellanic Cloud Microlensing Results from the First Two Years and the Nature of the Galactic Dark Halo," *ApJ*, 486, 697-726
- C. Alcock, D. L. Welch *et al.* 1997, "Is the Large Magellanic Cloud Microlensing Due to An Intervening Dwarf Galaxy?," *ApJ*, 490, L59-L64
- C. Alcock, D. L. Welch *et al.* 1997, "First Detection of a Gravitational Microlensing Candidate toward the Small Magellanic Cloud," *ApJ*, 491, L11-L14
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