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This report summarizes research activities in the astrophysics group at McMaster University from September 1, 1996 to August 31, 1997.

## 1. PERSONNEL

### 1.1 Faculty

The astrophysics group at McMaster operates in the Department of Physics and Astronomy. Faculty members include Professors William Harris, Ralph Pudritz, Peter Sutherland, and Douglas Welch and Associate Professor Christine Wilson (NSERC Women's Faculty Awardee). Welch became Chair of the Department of Physics and Astronomy on July 1, 1997 for an initial three-year appointment. He also was elected to the Organizing Committee of International Astronomical Union (IAU) Commission 27 - Variable Stars. He continues as a Council member of the American Association of Variable Star Observers. Sutherland continues to serve as Dean of Science. Pudritz took a half-year sabbatical leave at CITA (Jan.-Feb. 1997), where he was a Senior Fellow, and the Max-Planck-Institute für Astrophysik at Garching, Germany (March-Sept. 1997) where he was a Visiting Fellow. Pudritz continued as a member of CITA Council as well as the Canadian Gemini Science Steering Committee. Harris continues to serve as Past President of the Canadian Astronomical Society. Wilson continues to serve on the National Research Council's Herzberg Institute of Astrophysics Advisory Board and as a Director of the Canadian Astronomical Society. She completed her work as a member of the NRC Planning Committee for a New National Radio Astronomy Facility.

### 1.2 Graduate Students

A total of 9 graduate students were enrolled in the graduate program in astrophysics during this period (4 M.Sc. and 5 Ph.D.). Dean McLaughlin and Rashid Ouyed completed their Ph.D. work this year. Details on their topics are given below.

### 1.3 Graduated Ph. D. Students

Dr. Patrick Côté is a Sherman Fairchild Prize Fellow at Caltech. Dr. Phil Fischer is a Hubble Fellow at the University of Michigan, Ann Arbor. Dr. Kanan Patel is employed by the Royal Bank of Canada in the Risk Management Division. Dr. Jeff Secker is a Lecturer at Washington State University, Pullman. Dr. Charles Curry is an NSERC postdoctoral fellow at University of California, Berkeley. Dr. Patrick Durrell is a Visiting Assistant Professor at Case Western Reserve University. Dr. Dean McLaughlin is a Hubble Fellow at the University of California, Berkeley. Dr. Rashid Ouyed is a CITA National Fellow at Saint Mary's University.

### 1.4 Postdoctoral Fellows

Three postdoctoral fellows were members of the astrophysics group during this period. Dr. Chris Taylor worked with Dr. Wilson, Dr. Patrick Durrell with Dr. Harris (part time), and Dr. Rashid Ouyed with Drs. Pudritz and Sutherland. Dr. Taylor left the group in July 1997 to take up a postdoctoral fellowship at Universität Bochum, Dr. Durrell left in August to take up a visiting assistant professor position at Case Western Reserve University.

### 1.5 Current Information

Our Department maintains a home page that can be used to browse through current information on staff and students, graduate programs, curricula and research activities, including recent preprints. The URL is

*<http://www.physics.mcmaster.ca/>*

## 2. RESEARCH

### 2.1 Star Forming Regions in Galaxies

#### 2.1.1 Faint Blue Galaxies

Wilson and Combes (Observatoire de Paris) have obtained sensitive upper limits on the CO J=2-1 and CO J=3-2 emission lines for five faint blue galaxies with redshifts  $z \sim 0.5$  using the IRAM 30 m telescope. These observations would have been able to detect the luminous infrared galaxy IRAS F10214+4724 if it were located at this redshift and unlensed. However, they are not sensitive enough to detect the prototype starburst galaxy M82 or the HII galaxy UM448 if they were located at this redshift. The upper limits for the CO emission are consistent with between 19% and 66% of the total galactic mass being in the form of molecular hydrogen. Thus, the data shed little light on the ultimate fate of these galaxies, which depends on whether or not a significant amount of gas can remain bound to the galaxies through their current burst of star formation.

#### 2.1.2 Irregular Galaxies and HII Galaxies

Taylor collaborated with H. Koblunicky and E. Skillman (U. Minnesota) on  $^{12}\text{CO}$  J=1-0 observations of 7 low metal abundance HII galaxies with the NRAO 12-m telescope. These observations are the most sensitive ever obtained of HII galaxies and show evidence for a trend of low metal abundance galaxies having a lower L(CO)-to-M(HI) ratio than higher abundance galaxies. Taylor also collaborated with E. Brinks (U. Guanajuato) and T. Fritz and U. Klein (U. Bonn) on CO observations of a larger sample of HII galaxies using the IRAM 30-m telescope. To date these observations have provided very low upper limits on the CO emission, consistent with previous results. Together with S. Kohle and U. Klein (U. Bonn), Taylor started a program to study the molecular ISM in the Local Group dwarf irregular galaxy

WLM. The search of CO will be carried out near sites of recent star formation, and near the regions of highest column density of atomic hydrogen and will provide a highly detailed picture of the ISM in a low metal abundance galaxy.

Taylor and Wilson have used the SCUBA detector on the JCMT to study cool dust emission in HII galaxies. Very little is known about cool dust ( $T < 30$  K), even though it could constitute as much as 80% of the total dust mass. Observations of the first galaxy in the program, UM439, resulted in a 3-sigma upper limit of 16 mJy at 850 microns. This non-detection is below the level expected from an extrapolation of the IRAS 100 micron flux using a modified blackbody spectrum with  $T = 30$  K and the exponent of the dust emissivity = 1.5. Thus, there is no evidence for a cool dust component in this galaxy.

M. Sc. student Petitpas and Wilson have used CO observations obtained with the JCMT to study the effect of star formation on molecular clouds in the dwarf irregular galaxies IC 10 and NGC 6822. These low metallicity environments appear to be porous to UV radiation and allow for more efficient heating of molecular gas by nearby HII regions. The  $^{12}\text{CO } J=3-2/J=2-1$  ratio for the molecular cloud in NGC 6822 is higher than those found for IC 10 and M33 and is likely the result of its location inside a large HII region with low metallicity and low gas content. In IC 10, molecular structures with a variety of size scales all appear to be gravitationally bound, which may help explain the rather high star formation rate in IC 10.

### 2.1.3 Spiral Galaxies

Taylor and Wilson have used the Owens Valley millimeter interferometer to conduct high resolution  $^{12}\text{CO } J=1-0$  observations of giant molecular clouds (GMCs) in the nearby spiral galaxy M81. These observations are the first time individual GMCs have been resolved in a normal spiral galaxy outside the Local Group. M81 is also the earliest type spiral (Sab) in which individual GMCs have been observed. The clouds detected have molecular masses  $\sim 10^5 M_{\odot}$  and diameters of  $\sim 80$  pc. These clouds do not obey the size-linewidth relationship obeyed by GMCs in galaxies like the Milky Way, M31, and M33, and may instead be several associated smaller clouds. Because M81 has a steep gradient in metal abundance, further observations will be very useful in probing how the properties of GMCs vary with abundance. By comparing the data with observations of GMCs in M33, M31 and the Milky Way, potential dependencies of GMC properties upon the Hubble type of their host galaxies will be tested.

Petitpas and Wilson have used CO  $J=4-3$ ,  $J=3-2$ , and [CI] data to study the physical conditions and dynamics of the interstellar medium in the nucleus of M83. All maps exhibit a similar morphology with a double peaked appearance connected by an "elbow" of emission offset by  $\sim 30^\circ$  from the galactic bar observed at optical wavelengths, consistent with gas inflow along the bar collecting at the inner Lindblad resonance. This structure suggests that nuclear starbursts may occur even in galaxies where this inflow/collection occurs. The observed [CI]/CO  $J=4-3$  line ratios are very uniform, which suggests that the CO  $J=4-3$  emis-

sion is originating in the same hot photon-dominated regions as the [CI] emission. The CO  $J=4-3/J=3-2$  line ratios show significant variation, with the higher ratios occurring along an arc of active star forming regions. The high line ratios likely indicate optically thin gas created by the high temperatures caused by star forming regions in the nucleus of this starburst galaxy.

Wilson has measured the 492 GHz [CI] emission from four individual giant molecular clouds in the Local Group galaxy M33 using the James Clerk Maxwell Telescope. The column density ratio  $N(\text{C})/N(\text{CO})$  is similar to that observed in the Orion Bar, but smaller than values obtained for starburst galaxies. The [CI] line is found to be a more important coolant than the lowest three rotational transitions of CO for all the clouds in the sample. The [CI] luminosity does not appear to be enhanced significantly in two low-metallicity clouds, which may be due to the unusual ionization environment of the clouds, as these clouds are located near the giant HII region NGC 604. Similar data for the dwarf irregular galaxy IC 10 have been obtained in collaboration with Bollatto and Jackson (Boston).

### 2.1.4 Galactic Star Forming Regions

Wilson and Howe (U. Mass) have obtained observations over a large area of the Galactic molecular cloud M17 in the  $^{12}\text{CO}$  and  $^{13}\text{CO } J=3-2$  and  $J=2-1$  transitions at the James Clerk Maxwell Telescope. These data reveal systematic variations in the CO line ratios across the cloud, with both the  $^{12}\text{CO}/^{13}\text{CO } J=2-1$  and the  $^{12}\text{CO}/^{13}\text{CO } J=3-2$  line ratios being smaller by about a factor of two towards the center of the cloud than towards the edges of the cloud. By combining these data with data from the literature, it appears that there is a clear trend of increasing  $^{12}\text{CO}/^{13}\text{CO } J=2-1$  and  $J=3-2$  line ratios as one moves from Galactic molecular clouds to normal galaxies to starburst galaxies, similar to the trend seen previously for the  $^{12}\text{CO}/^{13}\text{CO } J=1-0$  line. The most likely explanation of the high line ratios for normal galaxies is a significant contribution to the CO emission by diffuse molecular clouds.

Ph.D. student B. Matthews and Wilson have observed the Class 0 source NGC 2264G with the Owens' Valley Interferometer in 3 mm continuum and the  $J=1-0$  transitions of  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$ . NGC 2264G is one of a number of protostellar sources identified to power an extensive outflow, and it has been suggested that NGC 2264G could be even younger than the prototypical Class 0 source, VLA 1623. The OVRO data reveal a compact line and continuum source at the position of the outflow. Extrapolating the 3 mm continuum flux gives a predicted flux at  $850 \mu\text{m}$  that agrees well with what is observed with a much larger ( $15''$ ) beam, which suggests that the continuum emission may arise in a compact envelope rather than a central disk. Matthews, Wilson, and Pudritz have also used the JCMT-CSO single baseline interferometer to observe a cluster of four Class 0 sources in Serpens. These sources reveal disk-to-envelope flux ratios similar to those seen in VLA 1623.

## 2.2 Star Formation Theory

Pudritz and his group of 3 Ph.D. graduate students J. Fiege, D. McLaughlin, and R. Ouyed have focused their research effort on the physics of the formation and structure of molecular cloud cores, the gravitational collapse of cloud cores modelled with “pure logotropic” and negative index polytropic equations of state, as well as the production of time-dependent MHD outflows from the surfaces of Keplerian accretion disks around black holes and protostars. The central aim of this research program is to produce an integrated theory of individual star formation encompassing initial conditions, gravitational collapse, outflow, and accretion disks. Visitors to Pudritz’s group this year were Dr. Alexander Dudorov from Chelyabinsk University in Russia, and Dr. Guy Pelletier from the Observatoire de Grenoble in France.

### 2.2.1 Accretion Disks

Pudritz and Dudorov are constructing a 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 magnetized disks which drive outflows could be advective so that their radial inflow velocities are a considerable fraction of the Kepler speed. Such self-similar models will have disk winds such as those modelled by Blandford and Payne (1982) and will be hot enough to emit X-rays. Thus, a single model which combines the observed facts that star forming regions generate X-rays and drive outflows, seems to be possible.

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 (1991). 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.

Pudritz, in collaboration with Kuperus and Janke at the MPA in Garching, is applying his ZEUS 2-D simulations of jets from accretion disks to the case of possible jet-like outflow from degenerate disks around merged neutron stars. This work could have considerable implications for the nature of gamma-ray bursts.

### 2.2.2 Jets

Ouyed and Pudritz, in collaboration with J. Stone (Maryland) employed the ZEUS 2-D MHD code to do time-dependent simulations of the acceleration and collimation of outflows from the surface of magnetized accretion disks. In all models, they assume that the disk is a fixed boundary condition for the problem, and create an accretion disk corona that is in initial hydrostatic equilibrium with the star, and in pressure balance with the accretion disk. The initial magnetic

configuration threading the disk and corona has zero current, and two initial configurations are investigated: one given by a potential solution and the other consisting of a uniform vertical field. The results show that the magnetic potential configuration launches an outflow that evolves into a steady state outflow when the rotation of the disk is commenced. The second configuration produces an episodic jet which generates knots close to the central object and which propagate down the length of the outflow. These knots are produced by a varying choke on the flow which is provided by the outflow’s toroidal magnetic field. Recent simulations find that by increasing the mass input rate from the disk into the disk corona, the disk winds go from being episodic to stationary independently of the magnetic configuration of the outflow. Future extensions of this work include the implementation of 3-D simulations in collaboration with Ouyed and Dr. David Clarke at Saint Mary’s.

### 2.2.3 Star Formation and Molecular Clouds

McLaughlin and Pudritz (MP) developed a theory for the structure of molecular cloud cores that fits the detailed observations of the internal structure of cores mapped out by Myers and Casselli (1995). Lizano and Shu showed that the turbulent part of the CO lines in molecular clouds might be modelled by a turbulent pressure with a logarithmic dependence on the density. They envisioned that low mass cores could still be fitted with an isothermal EOS. MP showed that the best fit to the data of both low and high mass cores comes from using a purely “logotropic” equation of state in which the pressure has the dependence on cloud density of the type,  $P/P_c = 1 + \ln(\rho/\rho_c)$ . The singular models of this type have a density dependence that is markedly more shallow than the traditional isothermal EOS being  $\rho \propto r^{-1}$ . MP went on to calculate the self-similar collapse of such pure logatropes models and have determined that the accretion rate is not constant with time but varies as  $\dot{M}_a \propto t^3$ . The collapse solutions show that small collapse speeds are expected, and that both solar and higher mass stars form in about the same time, of order 1 - 2 million years. These results have many implications for a theory of the IMF, which they have now started to investigate.

Fiege and Pudritz are working on a theory for the structure and fragmentation of filamentary molecular clouds. A great deal of attention has been paid to self-gravitating magnetized filaments over the years. However, most work features filamentary clouds in the absence of external pressure and with only poloidal magnetic fields. The data seem to suggest that both these extra ingredients are present in real filamentary clouds (eg. Bally 1989). We are constructing molecular cloud models which incorporate external pressure, and arbitrary magnetic field structure (eg. toroidal fields included) and are investigating their stability due to fragmentation. We are also working on the related problem of finding prolate MHD equilibria that could describe real cloud cores.

### 2.2.4 Cosmic Star Formation

During Pudritz’s sabbatical leave, he started to apply ideas of the formation of star clusters in self-gravitating clouds, to the general problem of star formation in hierarchical

cal models for galaxy formation (eg. CDM models). The recent excitement over the possible discovery of protogalaxies with cosmic star formation rates peaking at red-shifts near 2 is the driver for this work. Pudritz is generalizing the ideas of star 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. The purpose of the work is to understand how globular cluster systems around galaxies were produced as the galaxies underwent hierarchical merging. The effect of the new supernovae on the gas in merging dwarf galaxies is a topic of related interest in this regard.

### 2.3 Star Clusters

Harris is collaborating with Hesser, Stetson (DAO), Bolte (UCSC), Bell (U. Maryland) and Vandenberg (U. Victoria) in a study of the 6 Palomar-type globular clusters that are the most distant known members of the Milky Way halo. These clusters (NGC 2419, Pal 3,4,14, Eridanus, and AM-1) are widely believed to be systematically younger than the inner-halo clusters because most of them have horizontal-branch morphologies that are strongly affected by the 'second parameter' problem. WFPC2 photometry from HST Cycles 5, 6, and 7 is being employed to obtain much deeper photometric data for all these clusters than in any previous studies. This deep main-sequence photometry will permit age calibration for these clusters, relative to the more familiar inner-halo clusters, much more directly and will thus enable a stronger test of the age-gradient hypothesis. Our material for NGC 2419, the first of these to be studied, shows that it has the same age as M92 and the other low-metallicity halo clusters, to within  $\pm 1$  Gyr. In other words, star formation began all across the 200-kpc expanse of the halo at very much the same time. First results for three other clusters (Pal 3, 4, Eridanus) with moderately low metallicities and red horizontal branches show that they may be about 2 Gyr younger, on the average, than inner-halo clusters of similar metallicity such as M3 and M5, suggesting that the *range* in ages among the outermost-halo objects is larger. The WFPC2 images for the last two clusters in the program, AM-1 and Palomar 14, are to be obtained late in 1997.

Harris, Durrell, and graduate students Petitpas, Webb, and Woodworth completed a photometric analysis of the outer-halo cluster Palomar 2, from new CFHT CCD images. This cluster, virtually unstudied before this because of its unusual location toward the Galactic anticenter and high foreground reddening, turns out to be an intermediate metallicity cluster about 35 kpc from the Galactic center. Harris also updated his Web-based catalog of parameters for Milky Way globular clusters, which is publicly available at

<http://www.physics.mcmaster.ca/Globular.html/>

### 2.4 Stellar Populations and the Distance Scale

Harris and his colleagues continue their investigations of globular cluster systems in elliptical galaxies. New HST imaging data have been obtained for the central supergiant elliptical NGC 4874 in Coma, which will be analyzed for a comprehensive study of the cluster luminosity function and

metallicity distribution. Woodworth, for his M.Sc. thesis, is carrying out a similar analysis with data drawn from the HST archive for another Coma elliptical, IC4051. These results will be used to test the validity of the globular cluster luminosity function (GCLF) as a 'standard candle', and the presence of any bimodality or multimodality in the metallicity distribution.

Layden (U. Mich.), Schommer (CTIO), Sarajedini (KPNO), Durrell (Case Western) and Harris are currently studying the stellar populations of the nearby dE,N galaxy NGC 5206 using both ground-based data and HST observations. The images are also being used to study the nucleus of this galaxy, which is the closest example of a luminous nucleus in a dwarf elliptical galaxy.

Harris, Durrell, Secker (Wash. State), and Pierce (Indiana) are analysing HST *I*-band images of the nucleated dwarf elliptical galaxy VCC 1104 in the Virgo cluster. Our composite image (totalling 32000 seconds exposure time) clearly resolves more than a magnitude of the red-giant branch in this galaxy, enabling us to use the TRGB (giant branch tip) luminosity to calibrate its distance. Since the intrinsic precision of this method approaches  $\pm 0.1$  magnitude, it promises to yield the most accurate known method for establishing distances to the Virgo and Fornax clusters which are keystones in the extragalactic distance scale. Although Cepheids have comparable precision, the cores of the Virgo and Fornax clusters are defined by the dE,N and giant elliptical galaxies rather than the outlying Cepheid spirals, and so the TRGB method will reduce the intrinsic galaxy-to-galaxy distance scatter.

Harris, Durrell, Pritchett (U.Vic.) and Davidge (DAO) have undertaken a large *VI* photometric survey of the halo of M31 using the new 8K mosaic camera at the CFHT. This project is designed to trace out the shape, extent, and chemical composition profile of the M31 halo by direct photometry of the halo red giants. In a successful CFHT observing run in the fall of 1996 with the mosaic UH8K array camera, several half-degree deep fields were imaged along the minor axis and are now under reduction.

Welch collaborated with his MACHO Project colleagues Alcock, Alves, Bennett, Cook, Marhsall, Minitti (LLNL/CfPA), Griest, Guern, Lehner (UCSD/CfPA), Becker, Stubbs, Pratt (UW/CfPA), Allsman, Axelrod, Freeman, Peterson, Rodgers (MSO), Quinn (ESO) and Sutherland (Oxford), on several papers on microlensing and variables stars. Morgan (UNIowa) and Welch published a paper on beat Cepheid period ratios predicted using a linear, non-adiabatic pulsation code and made predictions for the period ratios that would be observed in SMC beat Cepheids if and when they are found. Rorabeck (MSc) completed his Master's thesis on the characteristics of the second-overtone mode of pulsation in Cepheid variables in the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) resulting in two papers submitted for publication. Welch continued to maintain and expand the archive of Cepheid photometry and radial velocities at the URL <http://www.physics.mcmaster.ca/Cepheid/>

Webb (MSc candidate), Welch and Wilson are studying the effects of metallicity on Cepheid luminosities using JHK

data acquired at the Canada-France-Hawaii Telescope with FWHM 0.6 arcsec seeing.

### 3. FACILITIES

Computing facilities in the astrophysics group consist of an extensive network of Sun/Sparc and SGI workstations with large amounts of disk space, tape drives, and laser printers. All parts of the system are fully networked and shared equally amongst staff and students.

McMaster University's W.J. McCallion Planetarium (a 50-seat theater with a Spitz A3P projector) is used frequently for school groups, public shows, and other community-group presentations. During the past year, approximately 100 shows were given. Planetarium shows are manned by faculty, graduate students, and by members of the Hamilton Amateur Astronomers and the Royal Astronomical Society of Canada, Hamilton Centre.

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Christine Wilson