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This report summarizes research activities in the astrophysics group at McMaster University from September 1, 1995 to August 31, 1996.

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, and Peter Sutherland; and Associate Professors Douglas Welch and Christine Wilson (NSERC Women's Faculty Awardee). Harris completed a two-year term as President of the Canadian Astronomical Society in June 1996 and will serve the next 2 years as Past President. Welch began a three-year term on the Canadian Time Allocation Committee of the Canada-France-Hawaii Telescope. Pudritz began a four-year term as a member of CITA Council. Sutherland began a five-year term as Dean of Science. Wilson began a three-year term on the National Research Council's Herzberg Institute of Astrophysics Advisory Board. She also began a three-year term on the board of the Canadian Astronomical Society. Wilson continues to serve on the National Research Council planning committee which is working toward a new national radio astronomy facility for Canada and as an ODIN astronomy scientist.

1.2 Graduate Students

A total of 8 graduate students were enrolled in the graduate program in astrophysics during this period (3 M.Sc., 5 Ph.D.). Charles Curry and Patrick Durrell completed their PhD work this year and Denise Kaisler completed her M.Sc. thesis. Details on their topics are given below.

1.3 Graduated Students

Dr. Patrick Côté is a Research Associate at the Dominion Astrophysical Observatory in Victoria, BC. 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. Charles Curry is an NSERC postdoctoral fellow at University of California, Berkeley. Dr. Patrick Durrell is employed as a sessional instructor at the University of Waterloo and as a part-time postdoctoral fellow at McMaster University.

1.4 Postdoctoral Fellows

Two postdoctoral fellows joined the astrophysics group in September 1995. Dr. Andrew Layden (Yale 1992) is working with Dr. Harris and Dr. Chris Taylor (Minnesota 1995) is working with Dr. Wilson. Details of their research are given below.

1.5 Current Information

Our Department maintains a ''home page'' accessible over the InterNet which 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 Stellar Populations and Distance Scale

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. During this time, the important paper on the microlensing optical depth toward the Large Magellanic Cloud (and its implications for the mass fraction of the halo in MACHOs) based on the first two years of data was submitted for publication (astro-ph/9606165). A binary lens event toward the LMC was modeled and interpreted as likely being an LMC member (astro-ph/9606012). The first example of a population II Cepheid in an eclipsing system (HV 5756) was found and an IAU Circular was issued to announce the next primary eclipse. Additional LMC double-mode Cepheids were identified bring the total to 73 of which 15 are fundamental/first overtone pulsators (astro-ph/9610024). A much larger sample of double-mode RR Lyrae stars was identified and analyzed (astro-ph/9608036). RR Lyrae stars in the recently identified Sgr dwarf galaxy were found in the MACHO Project bulge fields providing further evidence for the large extent of this nearby object (astro-ph/9605148). In collaboration with Pollard (SAAO) we also dramatically enlarged the sample of RV Tau stars in the LMC and showed that they are longer-period analogues of the W Vir stars. In collaboration with Clayton (UColorado) and Kilkenny (SAAO) we found three new, spectroscopically-confirmed R CrB stars in the LMC (astro-ph/9604177). Many additional candidates are now known. Rorabeck (M.Sc. candidate) is collaborating with the MACHO Project to identify singly-periodic second overtone (2H) Cepheids in the MACHO Project database. Fourier decomposition of the 44 known 1H/2H beat Cepheids in the MACHO Project LMC data show that lightcurve shape is correlated with mode of pulsation, and that the 2H mode is observationally distinct from the 1H and F modes over the known 2H period range. These findings define the characteristics of the 2H mode of Cepheid pulsation.

Dawson, Johnson (Trent), and Rorabeck completed a study on a technique for removing the kinematic bias inherent in proper motion survey studies of the Milky Way.

Monte Carlo simulations show the method is capable of recovering parent population kinematics to a high degree of accuracy when subsample 'catalogues' are small (200 stars), and when the subsamples are affected by both proper motion and magnitude limits. An application of the method to a subsample of the LHS catalogue provided an excellent result for thin disk kinematics. A large compilation of proper motion samples has been assembled from the literature, and work continues on disentangling the various stellar populations from the compilation before applying this method.

Morgan (UNIowa) and Welch submitted 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 (astro-ph/9607068). 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. Pierce (Indiana), Welch, McClure, van den Bergh, Stetson (DAO), and Racine (U Montreal) were awarded Cycle 6 HST to obtain photometry of Cepheids in the central Virgo spiral NGC 4571.

Welch acquired the original individual brightness estimates for variable stars in the LMC and SMC from Dr. Martha Hazen of Harvard College Observatory. Members of the Hamilton Amateur Astronomers and the Hamilton Centre of the Royal Astronomical Society of Canada have been reentering this data in electronic form. To date, the time series for 774 LMC variables can be found at the URL

http://www.physics.mcmaster.ca/HCO/

Welch continued to maintain and expand the archive of Cepheid photometry and radial velocities at the URL

http://www.physics.mcmaster.ca/Cepheid/

Layden completed a paper on the statistical parallax of RR Lyrae stars with collaborators Hanson (UCO/Lick), Hawley (Michigan State), Klemola (UCO/Lick), and Hanley (Michigan State). They compiled new data 213 nearby RR Lryae stars, divided the stars into thick disk and halo samples, and performed statistical parallax solutions to find the kinematics and absolute magnitudes (M_V) of these populations. For both populations, the kinematics were in excellent agreement with previous studies. Though the uncertainty on the thick disk M_V was large, precluding any measurement of the M_V–[Fe/H] relation, a precise value was determined for the halo, $M_V = 0.71 \pm 0.12$ mag, in agreement with the ''faint'' M_V values obtained by various other studies. Implications for the absolute ages of the Galactic globular clusters and for the distances to the Galactic Center and the LMC were given. It was also noted that values of the Hubble Constant, H_0, increase by 10% if recent Cepheid distances are recalibrated to the RR Lyrae LMC distance scale.

2.2 Globular Cluster Systems

Harris is collaborating with Hesser, Stetson (DAO), Bolte (UCSC), Bell (Maryland) and VandenBerg (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. However, to date none of these objects have direct age estimates via faint main-sequence photometry. We are using deep HST WFPC2 photometry from Cycles 5, 6, and 7 to obtain such data for all these clusters and thus investigate in a much more direct way the truth of the age-gradient hypothesis. This new material for NGC 2419, the first of these to be studied, shows that is has the same age as M92, the standard inner-halo cluster of the same metallicity as NGC 2419. With the best current isochrones, this age is 15 Gyr. Thus, at least for *some* of the outermost-halo objects, star (and star-cluster) formation clearly began just as early as in the much denser inner halo.

Harris and Davidge (DAO/Gemini) have completed a series of papers on deep near-infrared photometry of metal-poor globular clusters in the inner part of the Galaxy, from data taken with the CFHT Redeye camera in JK′. Color-magnitude diagrams in $J, J-K$ for the clusters M13, NGC 6626, M22, and NGC 288 reveal the main sequences and permit isochrone fits and age determinations which are shown to be consistent with those from optical photometry. Eventually, with deeper data it should prove possible to obtain ages from this type of near-IR photometry for the metal-poor, heavily reddened globular clusters in the Galactic bulge which are quite possibly the oldest objects in the Galaxy.

Harris and colleagues Phelps (Carnegie), Madore and Pevunova (IPAC) have collaborated with several amateur astronomers spread across the country (including Crute, Archinal, Wilson, and Skiff) to rediscover a long-lost globular cluster, IC 1257. This object, discovered more than a century ago, has always been listed as an open cluster but never studied, even though in several amateur publications it was mentioned as a possible globular cluster on the basis of its optical appearance and location on the sky. It came to our collective attention in August 1996, and it proved possible to obtain CCD imaging of it almost immediately. The color-magnitude diagram shows unequivocally that it is a globular cluster that is quite compact and highly reddened, and lies about 24 kpc from the Sun and 16 kpc beyond the Galactic center. Complete results of this study have now been written up. It raises the interesting question as to how many other such objects already in the catalogs still await correct identification.

Layden completed a paper with Sarajedini (KPNO) on CCD photometry of several ''young'' globular clusters. Color–magnitude diagrams were presented for Ter 7, Arp 2, and Rup 106, and metallicities and reddenings were derived from the shape and color of the Red Giant Branch (RGB). Systematic differences were noted with spectroscopic abundances derived from the Ca II triplet for these ''young'' clusters. It was suggested that systematic element ratio differences between these clusters and the ''old'' set used to calibrate the RGB and Ca-triplet vs. [Fe/H] relations might be the cause. Different [Ca/Fe] and [α/Fe] ratios might be expected if the ''young'' clusters experienced significantly different chemical enrichment histories.

Layden, Welch and Webb (M.Sc. candidate) embarked on

a systematic search for RR Lyrae variable stars in metal-rich Galactic globular clusters. A large amount of *VI* CCD data was obtained at CTIO in two observing runs. The goal is to search for cluster equivalents of the thick disk RR Lyraes seen in the field within several kpc of the Sun. Only one such cluster member is known: V9 in 47 Tuc, and it has an anomalously long period. A more complete cluster census is required before firm conclusions can be reached regarding the evolutionary paths of metal rich RR Lyraes in the field and in clusters. Layden also continued work on photometry of RR Lyraes in several galactic regions in preparation for spectroscopic (kinematic) followup.

P. Durrell completed his Ph.D. dissertation on the first systematic study of globular cluster systems (GCS's) in dwarf elliptical galaxies. The sample consists of 11 dE's in the Virgo cluster (work done in collaboration with Harris, D. Geisler [KPNO] and Pudritz) and the dE,N galaxy NGC 3115 DW1. The specific frequencies of the globular clusters in these galaxies is ~ 4, comparable to that found in both Local Group dE's and in giant elliptical galaxies. There are no systematic differences between the specific frequencies of dE and dE,N galaxies, suggesting similar paths of evolution. Furthermore, the GC mass spectrum has a slope similar to that found in all other (giant) galaxies to date, suggesting that the mechanism of GC formation is similar in galaxies of a wide range in mass and morphology. Metallicities (based on broad-band colors) have been derived for the GCSs around 3 of the galaxies, and in all cases the GCSs could not have been responsible for the observed differences between the metallicities of the GCs and the dE halo population. P. Durrell has also collaborated with S. Moehler (STScI) and U. Heber on a study of 2 sdB stars in the globular cluster M15, making it only the second globular cluster in which such stars have been proven to exist spectroscopically.

Harris and his colleagues continue their investigations of globular cluster systems in elliptical galaxies. Harris and M.Sc. student Kaisler completed a photometric study of the active cD galaxy NGC 1275, which involved a search for any trace of an old-halo globular cluster system. NGC 1275 – which is at the center of the Perseus cluster and is the host of a giant X-ray halo, a cooling flow, and large amounts of neutral HI accretion – is clearly the site of 'young globular cluster' formation in its nuclear regions, as shown definitively by the famous recent HST imaging study of Holtzman *et al.* Thus, it provides an interesting test case for the idea that any of these processes are responsible for globular cluster formation. Our results from deep CFHT imaging show that NGC 1275 does indeed have a recognizable old-halo population of clusters, but the specific frequency is quite normal for giant E galaxies (or even a bit below normal), at $S_N \sim 4$. A variety of interpretations are possible, but the most conservative one is that most of its globular cluster formation took place early on in a fairly conventional way, and that the current episodes of cooling flow and accretion will add to the cluster population in a fairly small way.

P. Côté (DAO), McLaughlin (Ph.D. candidate), and others are investigating the dynamics of the globular cluster system of M87 and implications for the structure of the dark-matter halo of that galaxy. One of the serendipitous offshoots of this project is the recent discovery of a probable CH star in the Galactic globular cluster M14. ω Cen is the only other globular known to contain this type of star, which shows strong Swan bands of C_2. All field CH stars, as well as those in ω Cen, are known to be binary systems, and the same is likely true of the new candidate in M14. In addition, all field CH stars have separations $a > 1$ AU or so. Since M14 and ω Cen are both low-concentration globulars, Côté *et al.* (1997, ApJ Letters, in press) suggest that the CH stars there may owe their existence to the long timescales for the shrinking and coalescence of hard binaries in such low-density environments.

2.3 Dwarf Galaxies

Layden, Sarajedini, Schommer (CTIO), Harris, and Durrell obtained *Hubble Space Telescope* images of the nucleated dwarf elliptical (dE,N) galaxy NGC 5206 in order to study the connection between the nucleus and the surrounding host galaxy. Preliminary analysis shows that the nucleus is resolved into a large star cluster ($R \approx 2$ pc if $D = 3.5$ Mpc), and that there is no color gradient ($\Delta(V-I) < 0.1$ mag) between the nucleus and the host. At face value, the latter suggests there is no age or metallicity difference between the two regions. However, age and metallicity are notoriously degenerate in broad band colors, so ground-based spectroscopy has been proposed in an effort to determine the evolutionary connection between the nucleus and host. Several globular clusters were resolved in the images, as were a large number of stars. The latter gives hope that an accurate distance can be determined from the I-band luminosity function.

Ph.D. student Secker, working with Harris, completed a study of the dwarf-E galaxy population in the Coma cluster of galaxies. Secker's results show that a definite color (metallicity) gradient exists among the numerous dE galaxies in Coma, such that the inner dE's have higher metallicity. This is consistent with models in which the proto-dwarfs further in to the center of the cluster are more constrained by higher external gas pressure, thus cannot eject enriched gas from early rounds of star formation as efficiently and end up systematically more enriched and more massive than the outer dE's. In addition, the dwarf-to-giant ratio (number of dE's per gE) is found to be just the same in Coma as in Virgo or Fornax, suggesting that Coma may have assembled from the amalgamation of slightly smaller clusters.

P. Durrell has completed surface photometry profiles for the 11 Virgo dE galaxies, including determinations of the magnitudes and upper limits (< 40pc) of the sizes of the nuclei present in 8 of the objects. In addition, 2 low-luminosity objects were discovered that are likely dwarf spheroidal galaxies in the Virgo cluster.

Taylor, in collaboration with D. Thomas, E. Brinks (NRAO) and E. Skillman (Minnesota) completed an HI survey of 17 low surface brightness (LSB) dwarf galaxies using the Very Large Array (VLA). LSB dwarfs are systems with a relatively low current star formation rate compared to HII galaxies, which are dwarfs experiencing a burst of massive star formation. The global HI properties of the LSB dwarfs such as HI mass and linewidth are similar to the properties of the HII galaxies, so the difference in star formation rates is

likely due to a local property such as gas density. Only 4 of the LSB dwarfs were found to have nearby HI rich companions, a rate three times lower than the HII galaxies. In a follow up study Taylor compared the statistical properties of the LSB sample to those of an HII galaxy sample from his Ph.D. thesis work. The difference in the rate of companion occurrence between the two samples is a genuine effect, not one caused by selection effects or observational bias. This result provides evidence that star formation in dwarf galaxies can be triggered by gravitational interaction with neighboring systems. The interaction–star formation connection has long been established for massive galaxies, but this is the first time it has been shown for dwarfs.

Taylor collaborated with H. Kobulnicky and E. Skillman (Minnesota) on ^{12}CO 1-0 observations of 7 low metal abundance HII galaxies with the NRAO 12-m telescope. Even though CO emission is believed to be dependent on metal abundance, previous work on HII galaxies had failed to find evidence for such a dependency, although the non-detections at low abundances did not provide significant constraints. The new observations are the most sensitive ever obtained of HII galaxies. They show evidence for a trend of low abundance galaxies having a lower L(CO)–to–M(HI) ratio than higher abundance galaxies, but result is only tentative because of the small sample size. Taylor and Brinks (NRAO) continued their project of observing a large sample of HII galaxies with a range of metal abundances in the ^{12}CO 1-0 line using the NRAO 12-m. This sample complements the previous one and will help establish or reject the previous result. Even more sensitive observations will soon be obtained using the IRAM 30-m telescope.

Taylor and Wilson began a program to use the JCMT to study cool dust emission in HII galaxies. Continuum observations in the submillimeter regime are sensitive to cool dust, with temperatures less than about 30 K, too cool to be detectable by the IRAS satellite. Consequently very little is known about cool dust, even though it could constitute as much as 80% of the total dust mass. Because HII galaxies are compact, the sky subtraction can be done accurately, as the telescope chop is guaranteed not to fall on part of the galaxy. Previous efforts to detect cool dust have been subject to controversy because they observed large spiral galaxies. With the observations at 450 μm and 850 μm dust temperatures will be estimated, allowing determination of the dust mass. From this the gas–to–dust ratios in these mini-starburst systems can be investigated.

2.4 Star Forming Regions in Galaxies

Taylor and Wilson are using the Owens Valley millimeter interferometer to conduct high resolution ^{12}CO 1-0 observations of giant molecular clouds (GMCs) in the nearby spiral galaxy M81. These observations will be the first time individual GMCs are resolved in a galaxy outside the Local Group, and M81 will be only the fourth spiral galaxy in which individual GMCs have been observed. Because M81 has a steep gradient in metal abundance, the observations will be very useful in probing how the properties of GMCs vary with abundance. It will also be possible to test the empirical CO–to–H_2 conversion relation derived by Wilson (1995). 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. Since variations in Hubble type are related to differences in star formation history, and star formation takes place in the molecular medium, there may exist differences in the GMC populations of the different galaxies.

Wilson, C. E. Walker (Arizona), and Thornley (Maryland) have completed a study of the J=2-1 and J=3-2 transitions of ^{12}CO and ^{13}CO in seven giant molecular clouds in the Local Group spiral galaxy M33. The observed ^{12}CO J=3-2/J=2-1 line ratio has a weak dependence on the star formation environment of the cloud, with large changes in the line ratio seen only for clouds in the immediate vicinity of an extremely luminous HII region. A large velocity gradient analysis indicates that clouds without HII regions have temperatures of 10-20 K, while clouds with HII regions have temperatures of 15-100 K, and the cloud in the giant HII region has a temperature of at least 100 K. Interestingly, the giant HII region appears capable of raising the kinetic temperature of the molecular gas only for clouds that are quite nearby ($<$100 pc). The continuous change of physical conditions across the observed range of star formation environments suggests that the unusual physical conditions in the cloud in the giant HII region are due to post-star formation changes in the molecular gas, rather than intrinsic properties of the gas related to the formation of the giant HII region. The results from this study of M33 suggest that similar observations of ensembles of giant molecular clouds in more distant normal spiral galaxies are likely to give meaningful measurements of the average physical conditions inside the molecular clouds.

Petitpas (M.Sc. candidate) and Wilson have observed the ^{12}CO J=2$-$1 and J=3$-$2 lines for the dwarf irregular galaxies IC 10 and NGC 6822. In addition, they have observed ^{13}CO J=2$-$1 for IC 10 and the first detection of the ^{13}CO J=3$-$2 transition in a Local Group galaxy. They find the CO line ratios in IC 10 are uniform and consistent with the average of M33 at the 1σ level. This indicates that the physical conditions in the IC 10 molecular clouds are similar to those in M33. By using the line ratios in conjunction with models they find the ^{12}CO J=3$-$2/J=2$-$1 ratio for NGC 6822 (which is higher than those found for IC 10 and M33) suggests that the ^{12}CO emission is optically thin in this region. This high line ratio requires a hydrogen density greater than 10^4 cm^{-3} and a kinetic temperature greater that 100 K. The ^{12}CO/^{13}CO J=3$-$2 line ratio in IC 10 MC1$-$2 indicates that the gas must have a rather high kinetic temperature of about 100 K.

Wilson and Howe (FCRAO) have obtained large area maps in the J=2-1 and J=3-2 CO transitions of the Galactic giant molecular cloud M17. The analysis of these data will provide the first measure of the global CO line ratios in a Galactic molecular cloud and will complement the extragalactic studies. Giannakopoulou, Fich (Waterloo), and Wilson are studying the properties of the molecular gas in the giant HII regions of M101 using both the JCMT and the Owens Valley Millimeter Array. These observations will allow us to determine the physical conditions in the molecular gas and

also to study the mass spectrum of any giant molecular associations in the giant HII region

Wilson has detected [CI] emission four individual giant molecular clouds in the Local Group spiral galaxy M33. Observations with the 11'' beam of the James Clerk Maxwell Telescope give peak temperatures of 0.2-0.3 K for the four clouds in the sample (MC 20, MC 32, NGC 604-2, and NGC 604-4). Comparing these data with published interferometric CO J=1-0 measurements yields an average [CI]/CO ratio of 0.12. The [CI]/CO line ratios for two clouds without optical HII regions are somewhat lower than for two clouds associated with HII regions. These observations of [CI] emission integrated over an entire molecular cloud will be used to determine how important the presence of massive star formation is to the formation of atomic carbon in clouds. Petitpas (M.Sc. candidate) and Wilson have obtained maps of [CI], CO J=4-3, and CO J=3-2 emission in the spiral galaxy M83. Preliminary analysis indicates a [CI]/CO J=1-0 line ratio similar to that seen for the M33 clouds. These [CI] data for M33 and M83 have been used to estimate [CI] line strengths for an ODIN survey of global [CI] emission in a large sample of external galaxies. Petitpas and Wilson have also obtained large maps of the starburst galaxy M82 in the J=3-2 transitions of CO, ^{13}CO, and C^{18}O, which will be used to study the column density and excitation of the molecular gas in the starburst, and in particular to determine the optical depth of the ^{13}CO line.

Gomez de Castro (Madrid), Pudritz, and Bastien (Montreal) completed a lengthy study of the interstellar polarization towards the high latitude clouds in the general direction of the galactic anticenter. These observations found that the magnetic field is perpendicular to the HI high latitude clouds. This field is interpreted as being a toroidal field that wraps around high latitude clouds. This structure could arise quite naturally if the high latitude clouds are contained within magnetic flux loops. Buoyant loops can rise to high galactic scale heights as a consequence of the Parker instability. They naturally attain a force-free magnetic structure in this process, which is dominated by a toroidal field.

Monin (Grenoble), Pudritz, and Lazareff (IRAM) completed ^{12}CO and ^{13}CO J=2-1 observations of the HL Tau/HH 30 region in the nearby Taurus molecular cloud. This work shows the existence of an extended red outflow lobe that is associated with HL Tau. The observed complexity of the molecular map on the scale of our map can be explained as possible outflows originating from several of the other young stellar objects in this region. They deduce that this stellar group can remain bound in spite of its vigorous outflows, and has a star formation efficiency of about 36%.

Pudritz and Wilson, in collaboration with Carlstrom (Chicago), Lay (Caltech), Hills (Cambridge) and Ward-Thompson (Edinborough) observed the ''Class 0'' protostar, VLA 1623 in order to determine whether or not a protostellar accretion disk could be detected. These observations were carried out using the JCMT-CSO single baseline interferometer. As these systems are believed to be within a dynamical time-scale old (less than 10^5 yrs), theory suggests that centrifugally supported disks are very small in comparison with larger, magnetically supported structures. These observations detected a compact source which probably corresponds to an accretion disk of radius $\leqslant$175 AU. The model suggests that this might be a magnetically supported structure (in the context of the work of Galli and Shu) of order 5×10^4 yrs old. This disk structure would have an inner centrifugally supported region which is large enough to support the production of collimated jets according to current models of outflows.

2.5 Theoretical Astrophysics

Pudritz and his group of 3 Ph.D. students Jason Fiege, Dean McLaughlin, and Rachid Ouyed have focussed their research effort on the physics of the formation and structure of molecular cloud cores, the gravitational collapse of cloud cores modeled 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.

Charles Curry completed his Ph.D. thesis, ''On the Global Stability of Magnetized Accretion Disks'' (Sept. 1995, McMaster University). Curry and Pudritz studied non-axisymmetric global instabilities in magnetized accretion disks. Purely hydrodynamic models for accretion disks show that non-axisymmetric instabilities exist in very narrow tori. These are thought to arise from the interaction of two surface modes, one on each of the inner and outer disk surfaces, as they are brought together. Our hydromagnetic results show that 2 types of global instability exist, one of which resembles the surface mode behavior in the hydro limit. The other unstable mode involve the appearance of Alfvén resonances in the disk, and the interaction of these Alfvénic type of waves as they propagate between resonances and the inner and outer disk surfaces. Of particular importance is that large scale non-axisymmetric modes can be generated over significant parts of Keplerian disks where the purely hydro theory shows disks to be stable. The important consequence of these calculations is that global magnetic field structures as well as angular momentum transport through the disk can arise as a consequence of these modes.

Alexander Dudorov (Chelyabinsk University, Russia) and Pudritz are constructing a model for the structure of magnetized accretion disks and their interaction with the magnetospheres of young stellar objects.

Ouyed and Pudritz, in collaboration with Jim Stone (Maryland) have employed the ZEUS 2-D MHD code in order 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 a 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 2 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. These results suggest that variability in outflows is not necessarily a consequence of disk instabilities, but could results from the dynamics of the disk outflow on its own.

Giant molecular clouds (GMCs) and clumps, which are the sites of star formation in the Galaxy today, are known to be self-gravitating and magnetized. They are supported against their own gravity in part by an internal turbulence which is characterized by gas velocity dispersions that *increase outwards* within a given cloud. McLaughlin and Pudritz generalized the classic Bonnor-Ebert stability analysis of pressure-bounded, self-gravitating spheres of isothermal gas, to include clouds with arbitrary barotropic equations of state (EOS). General physical arguments lead to the conclusions that (1) regardless of their exact EOS, GMCs and their most massive clumps must all be at their critical (Jeans) masses, and just marginally stable against large-scale gravitational collapse; (2) polytropic, or power-law, gas EOS are inadequate representations of interstellar clouds in general; and (3) the simplest model consistent with all the salient features of GMCs and clumps is a ''pure logotrope,'' in which $P/P_c = 1 + A\ln(\rho/\rho_c)$. A value of $A = 0.2$ is consistent with the observed mass and density contrasts between whole GMCs and massive clumps, and also gives an excellent fit to the observed dependence of velocity dispersion on radius in clumps is obtained with $A \simeq 0.2$.

Given this (phenomenological) description of the star-forming clumps in GMCs, McLaughlin & Pudritz (1997, ApJ, 476, in press astro-ph/9609080) obtained semi-analytical solutions for the inside-out (expansion-wave) collapse, beginning from virial equilibrium, of a logotropic sphere with a protostar at its center. It is found that the mass of the protostar grows in time as $M_0 \propto t^4$. By contrast, in a collapsing isothermal sphere, which is the standard model for theories of star formation, the central protostar would grow only as $M_0 \propto t$. Relative to an isothermal sphere, then, accretion onto a protostar is slower at early times, and faster later on, in a logotrope. This means that (1) low-mass protostars that are still accreting mass from their parent clumps (i.e., Class 0 sources) may be much older than expected in an isothermal collapse theory; and (2) stars with a wide range of masses form on rather comparable timescales ($\sim 1-3\times 10^6$ yr) in a logotrope. These results have implications for the origin and form of the stellar initial mass function, and for the process of star formation in clusters.

K. Durrell and Sutherland are currently modifying the Zeus2D magnetohydrodynamics code to include ambipolar diffusion, an effect of incomplete coupling between the neutral and ion fluids in partially ionized gas which allows the magnetic field to diffuse through the fluid. Its effects may be important in many areas of astrophysics as it can alter the configuration of the magnetic field lines. K. Durrell and Sutherland are using the code to extend previous studies of accretion disks.

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 been used frequently for school groups, public shows, and other community-group presentations. During the past year, approximately 150 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.

PUBLICATIONS

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