

Villanova University
Astronomy & Astrophysics
Villanova, Pennsylvania 19085

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This report covers the period from October 1999 to September 2000.

1. PERSONNEL

During the report period, 9/99-9/00, the staff included Assistant Professor Carol W. Ambruster, Instructor Larry DeWarf, Assistant Professor Edward L. Fitzpatrick, Post-Doctoral Fellow Patrick Godon, Professor Edward F. Guinan, Associate Professor Frank P. Maloney, Professor George P. McCook (Chairperson), Fulbright Fellow Dr. Ignasi Ribas, Research Assistant Professor Rex A. Saffer, Professor Edward M. Sion, and Research Associate Richard Wasatonic. Dr. Elizabeth R. Jewell served as Department Assistant.

John Bochanski, Joseph DePasquale, Paul DiTuro, Michael Dulude, Jonathan Hagsis, Colleen Henry, Joshua Lake, Kelly Lyons, Ira Nadalin, Christopher Pilman, Jeremy Sepinsky, Jeffrey Tracey, and Joel Urban served as research assistants.

2. INSTRUMENTATION

2.1 Automated Photoelectric Telescopes

The Fairborn Observatory, home of the Four College APT (FCAPT) is located in the Patagonia Mountains of AZ (Lat: +31 23 12; Long: -110 41 41). This 0.8m automated photoelectric telescope is operated by the Four College Consortium (FC) consisting of the The College of Charleston, The Citadel, University of Nevada-Las Vegas, and Villanova University. The FCAPT is supported by NSF grant AST95-28506 and AST-0071260.

2.2 Internet Access

The department's WWW address is: phy.vill.edu/astro; email address is: george.mccook@villanova.edu. Laboratory work for non-science majors can be found at: astro4.ast.vill.edu. This project is supported by the Pew Charitable Trusts.

3. CURRENT RESEARCH

3.1 Stellar Astronomy

Fitzpatrick and Nolan Walborn (STScI) completed a morphological study of the optical spectra of 20 high-luminosity, peculiar early-type stars. The results are discussed in PASP 112. The study is organized and discussed in terms of four categories of objects: WN-A or WNL stars, OB Iape or very late WN (WNVL) stars, iron stars, and B-supergiant Luminous Blue Variables (LBVs). Several objects in the earlier categories are also active or quiescent LBVs. Some (but not all) of these objects have been well-studied, and extensive references are provided, as are comprehensive spectral-line

identifications. Several new morphological relationships among the objects have been recognized through this presentation. In particular, attention is drawn to the occurrence of spatial pairing between nearly identical, unusual spectra, which may have implications for a particular mode of massive-star formation. This small sample includes one or both members of at least five such pairs. Physical explanations of these peculiar, probably-transitional spectra and the relationships among them are essential for a complete understanding of massive stellar evolution.

3.2 Interstellar Medium

In December 1999, Fitzpatrick received a Hubble Space Telescope Archival research grant to perform a study entitled *Confirming the Interstellar Abundance of Oxygen*. The element oxygen is an important tracer of the overall chemical composition of the Milky Way's interstellar medium (ISM) because it is a very abundant element, is only mildly depleted onto dust grains, and has absorption features in the observable UV spectral region. Recent studies have suggested that the interstellar abundance of oxygen is only about 2/3 that found in the Sun and this has been interpreted as indicating that the ISM is generally underabundant in elements heavier than hydrogen and helium compared to the Sun. This result has critical bearing on our view of chemical evolution in the nearby regions of the Galaxy. A potential weakness in these studies is that they depend on only a single absorption feature (at 1355.5977Å), for which the oscillator strength is theoretically determined and has a relatively large uncertainty. Fitzpatrick's program will provide an empirical (i.e., observational) determination of the critical 1355.5977 Å oscillator strength from an examination of interstellar oxygen absorption lines towards 6 nearby stars. The results of this program will place the oxygen analyses on a much firmer footing.

3.3 Eclipsing Binaries in the Large Magellanic Cloud

Guinan, Maloney, Fitzpatrick, DeWarf, and Ribas are continuing their study of carefully selected OB-type eclipsing binaries (EB) in the Large Magellanic Cloud (LMC). The goals of this program are (1) the determination of the fundamental properties (masses, radii, temperatures, luminosities, and metallicities) of the components of the binary systems, and (2) a precise measurement of the distance to the LMC. The properties of the stars are important for testing and constraining the results of stellar atmosphere, structure, and evolution theories. The LMC distance is a critical quantity since it forms the first rung on the cosmic *distance ladder* and is thus a key factor in determining the size scale of the universe. The study combines results from analysis of EB light and radial velocity curves with results obtained from the shape of the UV-optical spectral energy distribution, and in-

volves ground-based optical photometry and spectroscopy and space-based UV-optical spectrophotometry and spectroscopy.

Ribas, Guinan, Fitzpatrick, DeWarf, Maloney, P. Maunone (Villanova Un.), D. Bradstreet (Eastern Coll.), A. Giménez (Laboratorio de Astrofísica Espacial y Física Fundamental, LAEFF, Spain) and J. Pritchard (Mount John Un. Obs., NZ) completed a study of the orbital and physical properties of the LMC EB HV2274. HV 2274 is a particularly interesting system because it is detached, has an eccentric orbit, and shows rapid apsidal motion. Its distance had been determined previously by Guinan *et al.* (1998, ApJL, 509, L21). The values of the masses, radii, and effective temperatures are found to be $12.2 \pm 0.7 M_{\odot}$, $9.9 \pm 0.2 R_{\odot}$, 23000 ± 180 K for the primary star and $11.4 \pm 0.7 M_{\odot}$, $9.0 \pm 0.2 R_{\odot}$, 23110 ± 180 K, for the secondary. The age of the system (17 ± 2 Myr) and the helium abundance ($Y = 0.26 \pm 0.03$) were obtained by fitting the stellar data with evolution models of Claret & Giménez. Importantly, the results indicate that the size of the convective cores of the binary members are significantly larger than in “standard” evolution models, perhaps indicating the presence of enhanced convective core “overshooting.” The observed apsidal motion of the system — and the inferred internal mass distribution of the binary components — also confirms that larger core sizes are required to successfully model the binary’s properties. These results, which appeared in ApJ 528 demonstrate the power of the analysis technique to address issues of fundamental importance in stellar astrophysics.

Maloney, Fitzpatrick, Guinan, Kang (Sejong U.), Ribas, DeWarf, Bradstreet, and Sepinsky presented a preliminary study of the LMC EB EROS 1044 at the 195th meeting of the American Astronomical Society (Maloney *et al.* 1999, BAAS 31). This EB is one of a selected group of EBs in the Magellanic Clouds, begun with IUE and continued with HST. The chief aims are the determination of accurate temperatures, reddenings, and chemical abundances for the component stars. Twelve systems were observed with IUE during 1993-1995, mainly with the SWPLO camera (115-200nm). During 1996/97, HST/FOS observations (in the 115-480 nm range) were secured from ten of these systems. These UV results are being combined with radii and masses of the stars obtained from ground-based photometry and spectroscopy. The LMC eclipsing binary EROS 1044 (B2 V + B3 V; $V_{max} = +15.2$ mag; $P = 2.727$ d) was discovered as part of the photometric microlensing project using stars in the bar of the LMC. We have determined the orbital inclination ($i = 79$ deg.), and stellar physical properties (mass ratio, and fractional radii, temperatures, luminosities, and chemical abundances) from the Wilson-Devinney analysis of the light curve and from Kurucz (Atlas 9) model atmosphere fits to the HST/FOS spectra. Both components have similar properties: $r_1 = .23$, $r_2 = .32$, $T = 21300$ K, $\log g = 3.73$, $[\text{Fe}/\text{H}] = -0.20$, and $E(B-V) = 0.16$. These preliminary analyses, determined using ground-based radial velocity data, were encouraging enough for us to place this system on the target list for a radial velocity study with HST/STIS during cycle 9. This work is supported by grants from NASA (NAG5-7113),

HST (GO-06683), and NSF (RUI AST-9315365).

Fitzpatrick, Ribas, Guinan, DeWarf, Maloney, and D. Massa (Raytheon ITSS) completed an investigation of the properties of the LMC EB system HV982. Precise measurements were made of the stellar masses, radii, effective temperatures, and metallicities, as well as the interstellar reddening of the system. The distance to HV982 was found to be 45.6 ± 2.1 kpc. After correcting for the location of HV982, the implied distance to the optical center of the LMC’s bar is $d(\text{LMC}) = 45.9 \pm 2.1$ kpc. This result is entirely consistent with the earlier result for the LMC system HV2274. The results for these objects clearly demonstrate the power of EB systems as “standard candles.” The distance determinations are extremely robust, i.e., they have no reliance on zeropoint calibrations, are not subject to sampling biases, and are insensitive to stellar metallicity. In addition, the effects of interstellar extinction are explicitly determined for each object studied. The HV982 and HV2274 distances argue strongly in favor of the “short” LMC distance scale and suggest that the scale of the Universe is about 8% smaller than the commonly adopted result from the Hubble Space Telescope Cosmology Key Project. The HV982 study was presented at the June 2000 meeting of the American Astronomical Society (Fitzpatrick *et al.*, 2000, BAAS 32) and a paper describing the analysis has been accepted by the ApJ (astro-ph/0010526).

In December 1999, Guinan, Maloney, Fitzpatrick, DeWarf, Ribas, Bradstreet, and Gimenez were awarded 32 orbits with the Hubble Space Telescope during Cycle 9 (2000-2001) to carry out spectrophotometric and radial velocity studies of three additional systems well-suited for distance determinations: EROS 1044, EROS 1066, MACHO 053648.7-691700. All lie within or near to the LMC bar. The MACHO EB was selected to be close to the position (within 7 arcmin) of the supernova SN 1987A in the 30 Doradus complex and will provide a cross-check with analyses that determine the distance to the supernova utilizing observations of its expanding remnant. In addition, 8 nights with the Blanco 4-meter telescope at Cerro Tololo InterAmerican Observatory in Chile were awarded to Guinan *et al.* during December 2000 to obtain radial velocity curves for 6 LMC systems. The full analysis of these data potentially can result in a LMC distance measurement with a net uncertainty of $< 1.5\%$, as well as provide a detailed probe of the structure and spatial extent of this important galaxy.

3.4 Eclipsing Binaries in The Andromeda Galaxy

Ribas, Guinan, Fitzpatrick, A. Giménez (LAEFF, Spain), C. Jordi (U. de Barcelona, Spain), R. W. Hilditch (U. of St. Andrews, UK), and D. Valls-Gabaud (Observatoire Midi-Pyrénées, France) have begun a long-term project to study eclipsing binaries in The Andromeda Galaxy (M31). Accurate distance measurements to the Local Group galaxies are crucial to calibrating the cosmic distance scale and to determining the age and evolution of the Universe. As the first rung of the *cosmic distance ladder*, these galaxies serve as calibrators for distance indicators which reach far beyond the bounds of the Local Group. Once a Local Group galaxy’s distance is known, its various stellar populations (e.g., Cepheid variables) are available as potential “standard candles.”

M31 has become a first-class rung of the distance ladder with the advent of large aperture telescopes and high-efficiency instrumentation. The main advantages of M31 are a simple geometry and a chemical composition and morphology very similar to those of the Milky Way, and also a large and diverse stellar population that make it a robust anchor for the distance scale. Unfortunately, the distance to M31 is currently known to no better than 10–15%.

The work on the LMC distance has demonstrated that double-line eclipsing binaries can serve as excellent “standard candles.” Distances derived from eclipsing binaries are basically geometric and essentially free from many assumptions and uncertainties that plague other less direct methods. For example, Guinan *et al.* (1998, *ApJ*, 509, L21) and Fitzpatrick *et al.* (2000, *ApJ*, in press) recently obtained distances of 45.7 ± 1.6 kpc and 45.9 ± 2.1 kpc from the analysis of two LMC systems. The program of using eclipsing binaries as standard candles has been extended to determine an accurate distance to M31. As a first step toward this goal, a large volume of differential photometry is being obtained from the 2.5-m Isaac Newton Telescope (La Palma, Spain) for a sample of 21 eclipsing binaries. Also, an HST proposal has recently been submitted to carry out spectroscopy of two 19th mag early-B detached eclipsing binaries. HST/STIS low-resolution spectrophotometry (115–800 nm) will be used to determine T_{eff} , $[Fe/H]$, and A_{λ} . Based on previous experience, this project expects to reduce the uncertainty of the M31 distance to better than 5%, thereby firmly calibrating the Cosmic Distance Scale.

In addition to the distance determination, this program will yield the first direct determination of masses and radii of stars in M31. These results, combined with the luminosities, will be extremely useful for studying the structure and evolution of these stars, formed in an environment with a chemical history that may differ from that of the Milky Way. This will include an analysis of convective overshooting, mass loss, internal structure, and chemical enrichment law. Also, a direct empirical calibration of the M-L law for the more massive stars of M31 will also be possible. Finally, a complete characterization of the interstellar extinction in the line of sight of every target will be carried out. In particular, the strength of the 2175-Å bump and the slope of the far-UV rise will be studied.

3.5 Photometric Programs Conducted with the Four College Automatic Telescope

Guinan and McCook continue to coordinate the observations of different types of variable stars with the 0.8m Four College Automatic Photometric Telescope (FCAPT). DeWarf and Ribas are collaborating in several of the FCAPT programs. Most stars are observed with filters matched to the *UBVRI* or the Strömberg *uvby* systems. Some objects are also observed with $H\alpha$ or $H\beta$ narrow and intermediate-bands filters. Some representative Villanova FCAPT projects are: (1) “The Sun in Time” – photometry of about 15 solar-type stars of different ages to determine star spot coverages, rotation periods, activity cycles, (2) “Stellar Evolution in Real Time” that includes photometry of Nova Aql 1999b, and the rapidly evolving post-AGB stars – Sakurai’s Object and FG

Sge, (3) “Eclipsing Binaries as Astrophysical Laboratories” – the systems observed during 1999/00 include the high-mass eclipsing binaries: μ_1 Sgr, V380 Cyg (see below), 1 Per, VV Cep, and Y Cyg and the low mass systems: CM Dra, CU Cnc, V471 Tau. Results of searches for the light-time effect that would be produced in the arrival times of the eclipses by the gravitational pull are discussed elsewhere in this report, (4) “Chromospherically Active Single and Binaries” – the study of starspots and activity cycles of the following stars: V711 Tau, UX Ari, λ And, IM Peg, FK Com, and the dMe flare star AD Leo. (5) “Photometry of T Tauri Stars” - which includes SU and AB Aur and V410 Tau and a few other PMS stars (see below). (6) “Stellar Prototypes” - this program includes long-term photometry of the pulsating AGB star Mira, the bright Be star ω Ori, and observations of the X-ray (black hole candidate) binary Cygnus X-1 (see below).

In addition to these programs several other different types of variable stars are also being observed with the FCAPT. Coordinated observations of some of the program stars are being carried out with FUSE, Chandra, XMM, HST, and EUVE. The FCAPT programs are partially supported by NSF/RUI Grants. Several undergraduates have participated in this program during 1999/2000. They are John Bochanski, Joseph DePasquale, Jonathan Hargis (Eastern College), Joshua Lake (Eastern College), Joel Urban, Ira Nadalin, Jeremy Sepinsky and Jeffrey Tracey.

3.6 The Sun in Time Program

Multi-wavelength observations of a sample of nearby, single, solar-type stars with different ages and corresponding different rotation rates continue to be carried out by Guinan, McCook, DeWarf, Ribas, Güdel (ETHZ, Switzerland), and Messina (Catania Obs., Italy). Astronomy majors John Bochanski, Joseph De Pasquale, Paul DiTuro, Jonathan Hargis, and Ira Nadalin are also participating in the photometric aspects of the program. The stars in the program have spectral types of G0-G5 V and ages that range from ~ 70 Myr to ~ 9 Gyr. The ages of the program stars are determined from cluster or moving group memberships when possible. Other stars have ages determined from isochronal fits using evolutionary models and from activity-age relationships. The observations of the stars are being made from X-ray to radio wavelengths. Ground based photoelectric photometry continues to determine starspot coverage, differential rotation, and activity cycles. X-ray observations of a few of the youngest targets are being made with Chandra and XMM. Also, FUV spectrophotometry of π^1 UMa, κ^1 Cet, β Com, and β Hyi have been carried or approved for observations with FUSE.

Ribas, Guinan, Guedel (ETHZ, Switzerland) and A. Giménez (LAEFF, Spain) have completed irradiance tables for selected program stars that cover solar ages from ~ 70 Myr to 6.5 Gyr. X-ray (ASCA/ROSAT), EUV (EUVE), FUV (FUSE), UV (IUE/HST), and *UBVRI* (APT) radiometry of most of the targets that cover a wavelength range of 1 Å to 8600 Å has already been secured. This investigation focuses on the influence of the young Sun’s expected strong high-energy emissions on the photochemical evolution of early planetary atmospheres and ionospheres – in particular

on the erosion of Mars' primitive atmosphere. The FUV and UV ranges are especially important because they dominate the photoionization of key molecular species in planetary atmospheres.

4. V380 CYG

Guinan, Ribas, Fitzpatrick, and McCook, in collaboration with A. Giménez (LAEFF, Spain), C. Jordi (U. de Barcelona, Spain) and D. Popper (UCLA), have completed the analysis of the important eccentric eclipsing system V380 Cygni (HR 7567; $V_{max} = 5.68$; $P = 12.426$ days; B1.5 II-III + B2 V) from *UBV* differential photoelectric photometry obtained with the Phoenix-10 and the FC APTs. This bright eclipsing binary has properties that make it an important "astrophysical laboratory" for studying the structure and evolution of massive stars. The photometric elements obtained from the analysis of the light curves (using the Wilson-Devinney program) have been combined with the spectroscopic solution recently published by Popper & Guinan to yield the physical properties of the system components. The effective temperature of the stars has been determined by fitting IUE UV spectrophotometry to Kurucz model atmospheres and compared with other determinations from broad-band and intermediate-band standard photometry.

The values of mass, absolute radius, and effective temperature, for the primary and secondary stars are: $11.1 \pm 0.5 M_{\odot}$, $14.7 \pm 0.2 R_{\odot}$, $21\,350 \pm 400$ K, and $6.95 \pm 0.25 M_{\odot}$, $3.74 \pm 0.07 R_{\odot}$, $20\,500 \pm 500$ K, respectively. In addition, a re-determination of the system's apsidal motion rate has been done from the analysis of 12 eclipse timings obtained from 1923 to 1995. The apsidal motion study yields the internal mass distribution of the more luminous component. Using stellar structure and evolutionary models with modern input physics, tests on the extent of convection in the core of the more massive B1.5 II-III star of the system have been carried out. Both the analysis of the $\log g - \log T_{\text{eff}}$ diagram and the apsidal motion study indicate a star with a larger convective core, and thus more centrally condensed, than currently assumed. This has been quantified in form of an overshooting parameter with a value of $\alpha_{\text{ov}} \approx 0.6 \pm 0.1$. Also, V380 Cyg provides independent measures of the initial fractional helium abundance of the system (Y), which is an important and fundamental quantity but empirically difficult to measure. Finally, the tidal evolution of the system (synchronization and circularization times) has also been studied. The results of this study have recently been accepted for publication (Guinan *et al.* 2000, *ApJ*, 544, in press).

Early-type massive systems with at least one evolved component constitute a very important source of observational data for testing stellar structure and core convection. Such systems are scarce (due to strong observational selection effects) and gathering the required photometric and spectroscopic data is not easy (because of the typically long orbital periods – 10 days or more). The relative faintness of the secondary component also presents difficulties in the spectroscopic aspects of the problem. In spite of the observational challenges, these systems (although rare) have proved to be crucial tools and their study should be a priority in stellar astrophysics.

5. VERY LOW MASS ECLIPSING BINARIES: YY GEM, CU CNC, AND CM DRA

Ribas, Guinan, and collaborators G. Torres (CfA), A. Giménez (LAEFF, Spain), and D. Bradstreet (Eastern), are carrying out a program to study detached eclipsing binaries with M dwarf components. These low-mass eclipsing binaries are very important for a number of reasons: calibrating the mass-luminosity relation in the lower part of the H-R diagram, testing theoretical interior and evolutionary models for M-type stars, mass function studies ... Unfortunately, because of strong observational selection effects, only three eclipsing binaries, YY Gem (dM1 + dM1), CU Cnc (dM3.5 + dM3.5) and CM Dra (dM4.5 + dM4.5), are known to have components with masses significantly lower than solar. Yet the currently available photometric and spectroscopic data are scarce and of poor quality. Moreover, the analysis is often complicated because of the presence of spots in the stellar surfaces.

A program for determining accurate absolute dimensions of these benchmark stars has been started. A new high-quality radial velocity curve of YY Gem, with very similar components of about $0.6 M_{\odot}$, has been secured using the 61-inch reflector at Oak Ridge Observatory (SAO). The new radial velocity observations have been combined with published light curves and an analysis is under way. Preliminary results indicate that masses and radii with uncertainties below 1-2% will be determined for the components. Furthermore, CCD photometric photometry of YY Gem is also being obtained from the Bradstreet Observatory (Eastern).

CU Cnc was recently discovered to be a double-lined eclipsing binary with a period of 2.8 days and a very precise determination of the component masses (better than 0.5%) is available. To determine the absolute dimensions of this promising system, over 2400 photometric observations have been obtained from the FCAPT in the R and I bands, with a very dense coverage of the light curve. The combined analysis of the light and radial velocity is currently being carried out with the aid of the Wilson-Devinney code. The initial solutions indicate a system composed of two spotted stars with masses of 0.43 and 0.40 M_{\odot} and radii of 0.42 and 0.36 R_{\odot} in an orbit with an inclination of 86.9 deg.

Finally, the very least massive eclipsing binary known, CM Dra (two similar components of $0.23 M_{\odot}$), is being intensively observed from the Bradstreet Observatory (Eastern) and also using the FCAPT. The light curves, when combined with existing radial velocity data, will yield the absolute dimensions of the system components with an accuracy better than 1%. This will provide an excellent test of the stellar evolution models and the opportunity of estimating the helium abundance of this old system. Furthermore, the slight eccentric orbit of CM Dra permits a determination of the apsidal motion rate and, as a consequence, a powerful test of the internal structure of these fully-convective stars.

6. LOW-MASS TERTIARY COMPONENTS AROUND ECLIPSING BINARIES

Guinan, Ribas, and Villanova junior Bochanski have carried out an analysis of about 160 eclipse timings spanning over 30 years of the Hyades eclipsing binary V471 Tauri.

The results show a long-term quasi-sinusoidal modulation of its observed eclipse arrival times. The O–Cs have been analyzed for the “light-time” effect that arises from the gravitational influence of a tertiary companion. The presence of a third body causes the relative distance of the eclipsing pair to the Earth to change as it orbits the barycenter of the triple system. The result of the analysis of the eclipse times yields a light-time semi-amplitude of 137.2 ± 12.0 s, an orbital period of $P_3 = 30.5 \pm 1.6$ yr and an eccentricity of $e_3 = 0.31 \pm 0.04$. The mass of the tertiary component is $M_3 \sin i_3 \approx 0.0393 \pm 0.0038 M_\odot$ when a total mass of $1.61 \pm 0.06 M_\odot$ for V471 Tau is adopted. For orbital inclinations $i_3 > 35$ deg, the mass of the third body would be below the stable hydrogen burning limit of $M \approx 0.07 M_\odot$ and it thus would be a brown dwarf. Even for the minimum mass, however, the third body would be probably too massive to be a planet. What makes this brown dwarf candidate especially important is that its mass, age, and chemical composition can be simultaneously known. The age and chemical composition of the system are known from its membership in the Hyades cluster. The results of the analysis were presented in the 196th AAS Meeting in Rochester (Guinan *et al.* 2000, BAAS 32, 677) and have recently been accepted for publication in ApJ Letters (Guinan & Ribas, 2000, in press).

HST/FGS astrometry (to be combined with existing Hipparcos data) has been proposed to ascertain the presence and determine the properties of the tertiary component. When these astrometric measurements are available (covering half of the orbital period) they will unambiguously yield the orbital inclination and the semi-major axis with an error below 0.5 mas, corresponding to a few percent uncertainty of the tertiary object’s mass. This will represent the first direct dynamical mass determination of a brown dwarf with known age, chemical composition, and distance. Moreover, in the next several years it should be feasible to image directly V471 Tau C in the IR (using coronagraphic observations made with adaptive optics or observations made from space) as it moves toward maximum angular elongation from the eclipsing pair. Once these observations are carried out, and if V471 Tau C is indeed confirmed to be a brown dwarf, it will make an excellent benchmark for understanding the properties and evolution of these objects.

Guinan, Ribas, Bradstreet (Eastern), and Hargis (Eastern) have also analyzed 85 times of minimum light of the eclipsing binary CM Draconis (dM4.5+dM4.5, $P = 1.268$ days, $V_{\max} = 11.5$ mag) obtained between 1995 and mid-2000. With the possibility of planetary transits in this system (see IAUC 6423), I-band photometry has been carried out with particular attention being paid to observing the primary and secondary eclipses. In addition to searching for transit events, the eclipse minima have been monitored to look for evidence of the “light-time” effect. The observed–computed (O–C) timings (from a linear ephemeris) determined from the analysis of the eclipse minima show evidence of small (~ 10 – 20 s) variations on different time scales. The magnitude of the short-term variations appears to be correlated with the presence of wave-like disturbances in the outside eclipse portions of the light curves. These quasi-sinusoidal light variations are attributed to the presence of

star spots on these two rapidly-rotating dM4.5 stars. Simulations generated using Binary Maker show that the observed time of minimum light can be displaced typically by ~ 10 – 15 seconds from an uneven distribution of star spots on the surface of the star undergoing the eclipse. The preliminary results indicate that star spots can indeed account for the short-term non-periodic variations in the timing residuals. Modelling of the eclipses and eclipse times offer an opportunity to map the spots, as well their temporal evolution, on the surfaces of the two stars.

Although the short-term variations in the O–Cs arise most likely from spots, there appears to be a long-term variation in the seasonal averages with a period of several years. The semi-amplitude of this variation is about 10 seconds. If future observations confirm that this long-term variation in the O–Cs is indeed periodic, then it could be evidence for the presence of a sub-stellar third body in an eccentric orbit around the eclipsing binary.

6.1 Young Stellar Objects

DeWarf and Guinan, with Villanova senior I. Nadalin, continue their study of the classical T Tauri star (CTTS) SU Aurigae (HD 282624; G2 IIIe; $\langle V \rangle = +9.23$ mag; $\langle B - V \rangle = +0.83$). Long-term photometric observations are made using the 0.8 m FCAPT, in Arizona. This concentrated (nightly) photometry, beginning October 1993 and continuing to the present, is made with intermediate-band filters very closely matched to the Strömrgren *uvby* system. SU Aurigae is observed to undergo rapid and dramatic ($\Delta V \approx \Delta y \approx 0.40$ mag) light variations. These light variations appear not to be accompanied by spectral changes, which implies possible obscuration of the star by dust with properties similar to the interstellar medium (ISM). The light variations of SU Aur, like many T Tauri stars, are complicated. In addition to the short-term “dips” in the light curve, the star also varies on time scales of days, months, and years. In a previous paper by DeWarf, Guinan, and Radnor HS student T. Shaughnessy, the interstellar absorption of SU Aur was determined, and when combined with the Hipparcos distance, yielded estimates of its absolute magnitude and intrinsic colors (1998, *IBVS* 4551). These values place SU Aur about 1.8 mag above the main-sequence for its respective unreddened spectral type. Plotting SU Aur on pre-main sequence (PMS) evolution tracks yielded an age of about 4 Myrs and a mass of $1.9 \pm 0.1 M_\odot$.

CTT stars are pre-main sequence stars with extensive accretion disks. From infrared speckle interferometry taken by DeWarf and collaborator H.M. Dyck (then of Univ. of Wyoming) it is shown that the accretion disk and the possible concentrations of matter orbiting around SU Aur are observed nearly edge-on. In the currently analyzed APT photometric observations are possible short period variations in brightness that could arise from the rotational modulation of light by starspots. Many studies have established the rotation periods of T Tauri stars in this manner. They find a rotational period of about 1.7 days. Combining these results with the projected rotational velocity ($v \sin i$) yields a radius of about $2.2 R_\odot$. The results of this analysis have been submitted to the *IBVS* for publication.

In addition to observing SU Aur, differential photometry of its probable proper motion pair, AB Aur, is conducted at the same time. AB Aur is observed less frequently per night and shows only small light variations (± 0.07 in u and ± 0.03 in y). Other Young Stellar Objects that are intensively monitored are: GW Ori, V410 Tau, V833 Tau, V773 Tau, and V1331 Cyg.

6.2 Near Infrared and TiO Photometry of Pulsating Red Variables and Chromospherically Active Stars

Rick Wasatonic, Guinan and M.T. Mirtorabi (Inst. for Adv. Studies in Basic Science, Iran) continue long-term V-band and Wing three color near-IR/TiO photometry of pulsating red giant and supergiant stars. The observations started in 1995 by Wasatonic and Guinan; Mirtorabi joined in observing during 1998. The observations are being made with small telescopes: 25-cm and 35-cm reflectors located in Allentown, Pa (Wasatonic) and Zanjan, Iran (Mirtorabi), respectively. Photometric determinations of time-dependent stellar radius, temperature (T_{eff}) and intrinsic luminosity (L/L_{\odot}) variations are obtained from the near-IR observations. Observations also continue for a small sample of chromospherically active RS CVn-type spotted stars that include: λ And, IM Peg, V711 Tau, II Peg, and VW Cep. By analyzing the TiO-index formed from the Wing magnitudes and the V-mags and IR mags, the spot fill-factors (the fraction of surface spotted) are determined. The starspot and white light plage contributions and distributions can also be mapped over the surface of the rotating stars by modeling the light, TiO, and color variations.

The Wing three color near-IR photometric system consists of intermediate band filters centered on the TiO (γ 0,0) bandhead at 719nm and on two near-IR filters that are centered on "continuum" regions at 754nm, and 1024nm. A TiO-index and a near-IR color index ($\text{mag } \lambda 754 - \text{mag } \lambda 1024$) are formed from the observations and calibrated with T_{eff} and spectral type from numerous observations of standard stars. As first noted by Robert Wing, the 1024nm magnitudes closely approximate the apparent bolometric magnitudes for late-K to mid-M type stars. Thus the $\text{mag } (1024\text{nm})$ can be used as a proxy for $m(\text{bol})$ for cool stars. The following M supergiants stars are included on the observing program: α Ori (M1 Iab), α Sco (M1.5 Iab), CE Tau (M2-Iab), TV Gem (M2 Iab), and α Her (\sim M5 Ib), TV Gem (M2-Iab), and VV Cep (M1.5 Iab). Also, a few Mira and Mira-like variables are being observed. These targets include Mira (M5 - M9 III), R Leo (M4 - M9.5 III), and V CVn (M5 - M7 III-IIe). For each night of photometry, the temperatures of the stars are determined from the Wing TiO and near-IR color indices while the relative luminosity of the star is measured from the calibrated 1024nm magnitudes.

Initial results indicate that the red supergiants have different variability characteristics. Preliminary analysis of the observations shows that the semi-regular light variations of α Ori and the other early M supergiants predominantly arise from temperature variations rather from changes in radius. These initial results indicate that the light variations probably arise from non-radial pulsations and/or are produced by the waxing and waning of large bright convective structures (su-

pergranules?) on the stars' surfaces. Also, it has been found that the V-band light curves for these stars have essentially the same shapes as the TiO-index curves. This clearly shows that the V-band light curves of red supergiants and Mira variables are dominated by the large (temperature dependent) variations in the strengths of the TiO bands that occur within the V-bandpass. The results of the recent analysis of TV Gem have been completed and will be submitted for publication in early 2001. Papers have already been published for α Ori, α Her, CE Tau, and V CVn.

The exploratory program to observe several chromospherically-active RS CVn-type stars with the Wing filters is yielding some interesting results. There is an excess in the TiO-index (relative to that expected from spectral type or colors) for all of the program stars. The excess TiO-index has been modeled and can be easily explained by the presence of cool, dark (TiO strong) starspots that cover 20-50 percent of the surface area of the stars. An interesting result has been found from the analysis of the V, near-IR, and TiO-index light curves of λ And (G8 IV-III; $P_{\text{rot}} \sim 54$ -day) obtained over three years. The TiO-index light curves for this star have been modeled and permit the starspots to be mapped over the star's surface. However, the light curves at the other bandpasses are quite often different from the corresponding TiO-index light curves. A preliminary analysis indicates that the rotationally modulated continuum light variations are best fit from a combination of dark starspots and white light plages. In the case of λ And, the contributions to the V-band light curves appear to be dominated by white light plages that cover over 50% of the star's surface. Wing photometry of a similar star, IM Peg, was initiated this year to determine if this star displays similar behavior. Ignasi Ribas is contributing to this project during 2000 by computing synthetic TiO-indices and Wing near-IR colors from model atmospheres of cool stars. The research on near-IR photometry of long period red variables and chromospherically active stars is partially sponsored by NSF/RUI grants and NASA grants to Villanova University.

6.3 Variations of the Optical Light Curves of Cygnus X-1

Guinan, McCook, and students Jeremy Sepinsky and Joel Urban are obtaining new $UBVR$ and H- α light curves of the 5.6d X-ray binary (and blackhole candidate) Cygnus X-1. The observations are being made using the 0.8m FCAPT. Previous light curves are also being reviewed as part of this study. The preliminary study of the 2000 epoch $UBVR$ light curves indicates that the brightness variations of the system have changed since it was observed by Guinan and collaborators during 1977. As is well known, in the optical region Cygnus X-1 undergoes small periodic variations in brightness that arise from the tidal distortion of the O9Iab (the ellipticity effect) as it orbits the mass center of the binary. However, from the photometry obtained so far, it appears that the difference in phase between the light minimum at the superior conjunction (black hole candidate behind the star) and inferior conjunction (black hole candidate in front) is now ~ 0.44 phase apart. During 1977, the two light minima were separated by 0.48 phase. This apparent variation in the phase difference between the two conjunctions is best ex-

plained by apsidal motion that arises from General Relativity and Newtonian (tidal distortion) contributions as the stars move in an orbit with a small ($e \sim 0.05$) eccentricity. However, this is in apparent conflict with recent spectroscopy that indicates the orbit of CygX-1 is nearly circular ($e < 0.01$) and should not show a displacement of the two conjunctions from difference of 0.5 phase. It is hoped that additional observations will resolve this issue.

6.4 Zero-Age-Main-Sequence (ZAMS) K Dwarfs

Ambruster, in collaboration with B.E. Wood, A. Brown (CASA), and J. Linsky (JILA), analyzed local ISM absorption observed in the Lyman- α and Mg II h & k lines of six nearby members of the Pleiades Moving Group observed with the Goddard High Resolution Spectrograph on HST. The GHRS observations were originally made with the goal of studying the outer atmospheres of these stars, which are of special interest because they form a homogeneous sample: they are of essentially equal age (ZAMS), mass, and temperature (K0-K2), differing only in rotation period (0.38-6.9 d). The sample consists of: HD 1405, HD 17925, HD 82443, HD 82558, HD 220140, and HD 197890 (Speedy Mic). However, in order to derive accurate emission line fluxes from the GHRS and other data, it is necessary to correct for interstellar absorption, which strongly affects three important lines (Mg II h & k and Lyman- α), despite the fact that the stars are, with one exception, within 20 pc. For four of the six stars, an absorption component is detected with a velocity and column density consistent with the Local Interstellar Cloud (LIC). For HD 197890 (Speedy Mic), there is no observed component at the expected LIC velocity, or at the projected velocity of the G cloud, which is a nearby cloud in the general direction of the Galactic Center. It also seems doubtful that either of the two components seen toward HD 82558 are LIC or G cloud absorption. The total H I column density toward HD 82558 ($d = 18.3$ pc) is extremely high ($\log N_H = 19.05 \pm 0.15$), representing the largest average H I density detected for any line of sight through the nearby LISM ($n_H \sim 0.2 \text{ cm}^{-3}$). This is particularly remarkable considering that this star is only 39° from the 'interstellar tunnel' toward ϵ CMa, where column densities are an order of magnitude lower than this toward stars which are an order of magnitude farther away.

Ambruster continued analysis of the GHRS low-resolution spectra of these six stars, supplemented with archival GHRS observations of the very young dwarf AB Dor (which has a similar early K spectral class, although it is probably slightly younger than the other stars). Observational constraints on the radii of the stars, indicate that several have radii between 0.80 and $1.0 R_\odot$, and thus may still be slightly above the main sequence. Radii were calculated in three ways: 1) the Stefan-Boltzmann law, 2) the Barnes-Evans relation, and 3) $R \sin i$ (from observations of $V \sin i$ and the photometrically determined rotation period, P_{rot}). $R \sin i$ values emerged as the most reliable, despite uncertainties in i . The known observational uncertainties in both $V \sin i$ and P_{rot} were then used to calculate the minimum possible $R \sin i$ allowed by the observations. For 4 of the stars (Speedy Mic, HD 82558, HD 220140, and AB Dor), strict

lower limits to $R \sin i$ (in the range $0.80\text{-}0.88 R_\odot$) exceed the expected main sequence radii ($0.75\text{-}0.80 R_\odot$) of the stars (from standard tables). In turn, standard main sequence radii exceed Zero-Age-Main Sequence (ZAMS) radii, since stars increase in size during their stay on the main sequence. Thus it appears likely that these four stars are still slightly above, though very close to, the main sequence. Of the remaining three stars, HD 1405 and HD 17925 might or might not be above the main sequence, depending on currently unknown values of i , while HD 82443 most likely is on the ZAMS.

An unexpected result from the radius analysis is that these essentially ZAMS stars may be extensively, but uniformly, spotted, even at light curve maxima (starspot minima). This is true even when the historically brightest V magnitudes from the literature of the past 10-20 yr are used. Positing a brighter V magnitude (by up to $0^m.4$), and thus a brighter luminosity, seems to be the only way that radii computed from either the Barnes-Evans or Stefan-Boltzmann law can be made consistent with even the minimum lower limits to $R \sin i$.

From the adopted stellar radii ($R \sin i$, plus observational constraints on i , e.g., from published Doppler imaging) and the known distances (all but one star, HD 1405, have Hipparcos parallaxes), surface fluxes were calculated from observed fluxes via d^2/R^2 . Analysis of the rotation-activity relations derived from the final surface fluxes is currently in progress.

6.5 Archaeoastronomy

Ambruster gave an invited paper at the plenary session of the annual ARARA (American Rock Art Research Association) meeting (May 26-29, 2000, Heard Museum, Phoenix, AZ). The paper, to be published in the conference proceedings, presented new discoveries from a 1999 winter solstice field research trip to a site in eastern Chaco Canyon National Historical Culture Park, NM, which has been a focus of research with collaborator T. Hull (JPL) since 1993. Because of the well-known importance of the 4 cardinal directions in Navajo tradition and religion, plus occasional references to winter solstice in legends, it has been somewhat surprising that there are no references to the practice of observing or marking the solstices and equinoxes in the ethnological literature on the Navajo. However, in the last few years, several panels of 18th to early 19th c. Gobernador-style Navajo rock art at this Chaco Canyon site have been instrumental in confirming that observation of solstice and equinox sunrises, a practice usually associated with the Pueblos and Anasazi, was once important to at least some Navajo. Sky-related imagery, as well as Holy People, are present on several of the panels; and some rock art elements seem to be deliberately paired. But repetition also occurs on a grander scale: in December 1999, it was discovered that each solstice or equinox sunrise can be observed against the identical horizon feature from it two nearby sites: there are 2 winter solstice sunrise observation sites (1 Navajo and 1 Anasazi), 2 summer solstice sunrise sites (again, 1 Navajo and 1 Anasazi), and 2 equinox observation sites (both Navajo). At this site, it all six boulders with significant rock art mark a place from which to observe solstice or equinox sunrises against one of the few

distinct cliffs on a generally featureless eastern horizon. Conversely, as seen from all boulders it without significant rock art, no matter how smooth and appealing the surface, solstice or equinox sunrises appear at flat or otherwise nondescript places on the eastern horizon. That is, rock art appears to have been consciously carved only on boulders that provided clear confirmation of the arrival of solstices or equinoxes. The rock art on each of the Navajo panels is very different, with little or no overlap of imagery or symbols. This might suggest that each panel served a different ceremonial function: either different parts of a specific ceremony, or different ceremonies altogether. The winter and summer solstice Navajo rock art panels incorporate seasonal motifs into the rock art itself: two Sun shields as well as the traditional Navajo constellations for November and December on the winter solstice panel, and plants on the summer solstice panel. While not season specific, Anasazi spirals, such as those on the Anasazi summer solstice panel, are known to occasionally be associated with the Sun. The two Navajo Equinox sunrise sites, perhaps because they pertain to both spring and fall, do not seem to contain season-specific imagery, although they do contain clear references to the Sun in the form of a 'Sun Shield' on one panel, and 2 or 3 sun glyphs on the other. The repetition of important symbols in the rock art at this site, as well as the pairing of the sites themselves, fits with the Navajo use of repetition to enhance spiritual power. The pairing of elements is most precise on the Navajo winter solstice rock art panel (2 Sun shields, 2 each of the constellations marking November and December, 2 Holy People), but repetition is also present, though not always in multiples of two, on one of the Navajo Equinox panels (3 completed Holy People, two completed circles with triangular rays, several downward pointing arrows) and the Navajo summer solstice panel (at least two plants). Finally, this site provides an informative window on 18th c. Navajo attitudes towards the Anasazi ruins in their midst: as is sometimes seen in the Dinetah, Navajo and Anasazi sites are intermingled on distance scales as small as a few tens of meters. This proximity is found in both residential and ceremonial contexts: there is, for example, both a Navajo sunwatching site and an Anasazi sunwatching site in each of the winter solstice and summer solstice pairs. This, plus the presence of both Navajo and Anasazi residential features suggests that, in contrast to later historical times, 18th c. Navajo in this part of Chaco Canyon were not uncomfortable living among Anasazi remains.

An overall map of the distribution of surface features at the site, now 80% complete, is being done by GPS in UTM coordinates. A primary datum was selected at a point along the Park boundary fence. The site map has been generated relative to this datum, and a series of sub-datums; the altitude and UTM offsets of the sub-datums from the primary datum have a precision of approximately 1 meter. Each of the boulders and surface features, as well as site topography information, are recorded in this manner. All measurements utilize hand-held Suunto compasses and clinometers which have been calibrated both absolutely, and against each other. The precision of these azimuth/altitude measurements is between 0.5 and 1 degree, which is sufficient for the purposes

of the project. Using horizon measurements and the precisely known position of the Sun at winter solstice sunrise, a magnetic declination of 11.9 degrees is determined for the site; this correction has been applied to measured azimuths and altitudes for comparison with published solar positions.

6.6 KPD 2146+4117

Saffer and collaborators P. Bergeron & F. Wesemael (2000, *PASP*, 112, 837) made a new optical spectrum and model atmosphere study of the cool DBA white dwarf KPD 2146+4117, discovered in the Kitt Peak Downes colorimetric survey. The analysis shows that this star should be reclassified as a helium-strong subdwarf B star. The parameters we derive, $T_{eff}=34,300$ K, $\log g=6.1$, and $\log y = -1.0$, place it squarely within the sample of such objects studied by R.A. Saffer and coworkers.

6.7 EC 14026 Seismology

Saffer and collaborators M. Billeres, G Fontaine, P. Brassard, S. Charpinet, & J. Liebert reported the discovery of multiperiodic luminosity variations in the hot B subdwarf KPD 1930+2752. This star was selected as a potential target in the course of an ongoing survey to search for pulsators of the EC 14026 type. A model atmosphere analysis of the time-averaged optical spectrum of KPD 1930+2752 indicates that this star has $T_{eff}=33,280$ K and $\log g=5.61$, which places it well within the theoretical EC 14026 instability strip. At least 44 harmonic oscillations are seen in the light curve, with periods in the range 145-332 s, and amplitudes in the range 0.064%-0.451% of the mean brightness of the star. In addition, the light curve is dominated by a nearly sinusoidal variation with a period of ~ 4108.9 s and amplitude of $\sim 1.39\%$. This latter variation is unique among the known EC 14026 stars. This relatively slow luminosity variation is likely due to the ellipsoidal deformation of the sdB star in a close binary system containing a faint invisible companion (possibly a white dwarf). Using a new period-matching technique based on a genetic algorithm, the dense observed period spectrum in the 145-332 s interval is shown to be compatible with a theoretical low-degree p-mode spectrum that is rotationally split in a star rotating with a period of ~ 8217.8 s, the value expected from the ellipsoidal effect invoked to explain the observed long-period variation. This interpretation awaits the test of time-resolved spectroscopy. If confirmed, the potential of KPD 1930+2752 as a laboratory for EC 14026 seismology will become immense.

6.8 NGC 1818

Saffer and collaborators M. Burleigh, G. Gilmore, & R. Napiwotzki analyzed an optical spectrum of the Elson *et al.* candidate luminous white dwarf in the young LMC cluster NGC 1818. The analysis shows conclusively that it is not a degenerate star. A model atmosphere fit gives $T_{eff}=31,500$ K and $\log g=4.4$, typical of a normal main-sequence B star. However, if it is a true LMC member then the star is underluminous by almost 3 magnitudes. Its position in the cluster color-magnitude diagram also rules out the possibility that this is an ordinary B star. The luminosity is, however, con-

sistent with a ~ 0.5 solar mass post-asymptotic giant branch or post-extended horizontal branch object, although if it has evolved via single-star evolution from a high-mass (7.6-9.0 solar mass) progenitor then we might expect it to have a much higher mass, ~ 0.9 solar masses. Alternatively, it may have evolved in a close binary. In this case the object offers no implications for the maximum mass for white dwarf progenitors, or the initial-final mass relation. Finally, we suggest that it could in fact be an evolved member of the LMC disc, and merely projected by chance on to NGC 1818. Spectroscopically, though, we cannot distinguish between these evolutionary states without higher resolution (echelle) data.

6.9 Field White Dwarfs

6.9.1 White Dwarf Mass Distribution, Gravitational Redshifts & Kinematics

Sion, with N. Silvestri, T.D. Oswalt and M.A. Wood (FIT) and I.N. Reid (U Pa.) examined the mass distribution, gravitational; redshifts, radial velocities and space motions of white dwarfs in common proper motion binaries. They derive a mass distribution with a mean mass of $0.68 \pm 0.04 M_{\odot}$. This distribution has a slightly higher mean and larger dispersion than most previous white dwarf studies. They hypothesize that this is due to a higher fraction of cool white dwarfs in their sample. They find that samples made up of predominantly cool, old white dwarfs tend to have bimodal distribution with a second mass peak at $\sim 1.0 M_{\odot}$, which skews the mean toward a higher mass. Both the mean and individual white dwarf masses they report are in better agreement with those determined from model atmosphere spectroscopic fits to line profiles than with most previous gravitational redshift studies of cool white dwarfs. Their results indicate that measurement biases and weak geocoronal lines in the observed spectra may have contaminated previous redshift measurements. They also published a list of complete space motions for 50 wide binary white dwarfs, derived from radial velocity measurements of their non-degenerate companions. They found that the UVW space motions and dispersions of the common proper motion binaries that contain white dwarf components are consistent with those of old, metal-poor disk stars.

6.9.2 White Dwarf Local Space Density

Sion, in collaboration with J. B. Holberg (LPL West, U.Az) and T.D. Oswalt (FIT) used the most recent version of the Catalogue of Spectroscopically Identified White Dwarfs listing 2249 white dwarf stars to determine the space density of white dwarfs. Among their sample are 118 white dwarfs that have either reliable trigonometric parallaxes or color-based distance moduli which place them at a distance within 20 pc of the Sun. Most of these nearby white dwarfs are isolated stars, but 35 (30% of the sample) are in binary systems, including such well known systems as Sirius A/B, and Procyon A/B. There are also three double degenerate systems in this sample of the local white dwarf population. The sample of local white dwarfs is largely complete out to 13 pc

and the local density of white dwarf stars is found to be $5.5 \pm 0.8 \times 10^{-3} \text{ pc}^{-3}$ with a corresponding mass density of $3.7 \pm 0.5 \times 10^{-3} M_{\odot} \text{ pc}^{-3}$.

The local sample possesses several advantages over previous estimates of the white dwarf density derived from other samples. The chief advantages are its completely volume-limited nature and relatively high level of apparent completeness. It does, however, suffer at present from a rather low sample size. This limitation is likely to be diminished if the present zone of completeness is increased from 13 pc to 20 pc. They intend to do this as part of the NSTARS program which is aimed at discovering and cataloging the stellar population within 20 pc of the Sun. The primary statistical uncertainty in all present estimates of the space density of white dwarfs comes from the small sample size of typically ~ 50 stars. Wood & Oswalt (1998) used Monte Carlo calculations to estimate that for sample sizes of $N \sim 50$ white dwarfs, uncertainties in n_{WD} of $\sim 50\%$ are expected. There also exists a modest systematic uncertainty due to the possibility that future searches and surveys may lead to the discovery of additional white dwarfs within 13 pc. The slight north-south asymmetry in the number of stars within 13 pc, hints at this possibility. Thus, while it is possible that the future may bring a modest increase in the number of white dwarfs in this volume, it is highly unlikely, given the quality of the present distance estimates, that the number of known stars will significantly decrease. Thus, their number and mass density estimates can be regarded as firm lower limits.

6.9.3 Surface Compositions of the Local White Dwarfs

The types of white dwarf stars which make up the local sample are also of interest. This is in part due to the fact that the population ratio of the two primary spectral types, the H-rich DA stars and the non-DA stars appears to undergo several changes as a function of effective temperature. That is, white dwarfs appear to change spectral classification based on the dominant atmospheric species as they cool. One of the most obvious manifestations of this is the decline in the DA to non-DA ratio. At temperatures of 20,000 K and above, this ratio reaches a value of 7:1 but declines to about 1:1 and lower for white dwarfs near 5,000 K to 4,000 K (Sion 1984; Bergeron, Ruiz & Leggett 1998). In the local sample we find the DA to non-DA ratio to be 1.2. This is consistent with the fact that there are few white dwarfs with $T_{eff} < 20,000$ K in the local sample.

6.9.4 The Web-Based Villanova Catalog of White Dwarfs

During the report period, McCook constructed the web-based version of the Villanova Catalogue of *Spectroscopically Identified White Dwarfs* by McCook and Sion. McCook and Sion received a three-year grant from the NASA Applied Information Systems Research Program to develop an interactive web-based user interface with hyperlinks to citations for all data. This can be accessed at www.phy.villanova.edu/astro/WDCatalog/index.html. This catalog is also the primary observational data source for the White Dwarf Database being developed by J. Holberg (U. AZ) and collaborators at the Lunar and Planetary Laboratory West in

Tucson. This will eventually include masses, radii and finding charts for all of the known white dwarf stars.

6.10 White Dwarfs in Post-Common Envelope Binaries

Villanova senior astronomy major, Colleen Henry, and Sion considered the thermal history of the magnetic white dwarf in the Hyades, pre-cataclysmic, eclipsing-spectroscopic binary, V471 Tauri. With $T_{eff} = 35,000\text{K}$, ($M_{wd} = 0.8M_{\odot}$), its cooling age is only 7.8×10^6 years compared with the mean cooling age of Hyades single white dwarfs of 9×10^7 years. If its formation was essentially coeval with the single Hyades degenerates, then V471 Tauri is 13,000K hotter than their average T_{eff} (19,680K). This amount of heating by accretion is in the same regime as that experienced, on average, by white dwarfs in cataclysmic variables (Sion 1999, PASP, 111, 532). They compared the positions of the Hyades degenerates in the HRD with a Bondi-Hoyle locus of constant accretion, as discussed by Castellani & Panagia (1971). They considered several possible physical explanations for the puzzling cooling history of the V471 Tauri degenerate. These include the possibility of an ancient nova with limit cycle evolution, steady proton-proton nuclear burning providing its surface luminosity, and radial accretion heating maintaining its observed T_{eff} . For steady hydrogen burning, an accretion rate $\dot{M} = 1 \times 10^{-11} L_{\odot} / X_h = 2 \times 10^{-12} M_{\odot} / \text{yr}$ is sufficient to account for the present T_{eff} .

How much accreted mass is needed to spin the white dwarf up to its present rotation (120 km/s)? Substituting numerical values, we find that, for an initial velocity of 0 km/s the white dwarf would have accreted $7.8 \times 10^{-3} M_{\odot}$ to be spun up to its present rotation rate. This is an upper limit since we assumed zero rotation initially. If the initial white dwarf rotation was 50 km/s (rapid for a field white dwarf), then $\Delta M_{acc} = 5.6 \times 10^{-4} M_{\odot}$. The only time the white dwarf could be accreting at a rate similar to cataclysmic variables is just after emergence from the common envelope when the K-dwarf was bloated and could have filled its Roche lobe. The relaxation timescale for the bloated late-type dwarf following its emergence from the common envelope is of the order of 10^4 years (Hjellming & Taam 1994). It is during this phase that the white dwarf could have accreted at a rate comparable to cataclysmic variables.

Sion, Sean O'Brien (STScI) and Howard E. Bond (STScI) completed the analysis of 12 *Hubble Space Telescope* GHRS medium resolution spectra in the $\text{Ly}\alpha$ region toward the Hyades white dwarf (WD) + K2 dwarf eclipsing binary, V471 Tauri. The spectra were obtained at first and third quadrature in the binary orbit and provide a rare opportunity to determine a dynamical mass for a nearby WD star. Fits to the $\text{Ly}\alpha$ absorption profile yield a velocity semi-amplitude $K_{WD} = 164.0 \pm 3.5 \text{ km s}^{-1}$. Using the known velocity semi-amplitude of the K dwarf, we derive stellar masses of $M_{dK} = 0.93 \pm 0.04 M_{\odot}$ and $M_{WD} = 0.84 \pm 0.02 M_{\odot}$ for the K dwarf and WD, respectively. Both component masses are higher than has been assumed in most previous investigations. However, with its radius previously determined, the WD is now in excellent agreement with the theoretical mass-

radius relation. We also derive the orbital inclination ($77.5 \pm 0.7\text{deg}$), component separation ($3.30 \pm 0.06 R_{\odot}$), and the fraction by which the K dwarf fills its Roche lobe (77%). The newly determined orbital parameters allow us to confine the fundamental CE efficiency parameter to the range $0.1 < \alpha_{CE} < 0.6$, implying a relatively high rate at which CE evolution creates close binary systems.

6.11 White Dwarfs in Cataclysmic Variables

6.11.1 The Accretion Disc Boundary Layer in Cataclysmic Variables

Godon is carrying out a numerical study of gaseous astrophysical discs as found in some binary systems (Cataclysmic Variables - CVs), in which a star is losing mass that is transferred to its companion (a white dwarf). This matter forms a flat disc around the white dwarf and, due to viscous dissipation, the matter in the disc is slowly accreted onto the surface of the white dwarf. The main unsolved problem in these systems is the boundary layer region between the fast rotating inner edge of the disc and the slowly rotating stellar surface. In this region, the disc is expected to slow down until its velocity matches the velocity of the stellar surface. The disc loses kinetic energy which is expected eventually to be emitted by the inner disc. The luminosity of the inner edge of the disc predicted by one-dimensional simulations is large; however, two decades of observations have not shown any evidence of a luminous (and hot) boundary layer. He is developing a two-dimensional hydrodynamic code to carry out two-dimensional simulations of the boundary layer region to solve the long standing problem of the missing boundary layer.

The way the matter is accreted from the disc onto the star has direct consequences on other important processes. The accreted material, after it accumulates onto the surface of the white dwarf, undergoes a thermonuclear runaway - TNR (nova). In order to model correctly the TNR event, one has to know whether the material from the disc has spread toward the poles of the star or has remained in the equator. It is not known whether the equatorial material on the star is accelerated (as some observations suggest) or not. Convective currents due to Eckman pumping (or even turbulence due to the shear) in the outer envelope of the star (and in the accreted envelope) could take place, and would mix the freshly accreted material (Hydrogen-H) with heavier elements (e.g., P, Al, ...) found in the star. During a TNR, the heavy elements would be ejected in the interstellar medium and affect the composition of the interstellar gas. The problem of the BL is therefore important not only to explain the observations of CV systems, but also to predict the TNR events, the mixing of the elements in the outer envelope of the white dwarf and the heavy elements ejected in the interstellar medium, and most importantly this would have significant implications in the theory of STAR FORMATION. In this picture, the heating of the star due to BL radiation and advection of energy would also affect the TNR event.

6.11.2 Far Ultraviolet Spectroscopy of CV White Dwarfs

Sion continued to concentrate on far *UV* spectroscopy of faint exposed white dwarfs (WDs) in cataclysmic variables (CVs). This work has provided fundamental new information on the underlying white dwarf accreter. Among the new parameters and insights are white dwarf rotation rates, T_{eff} , $\log g$, chemical abundances of their accreted atmospheres, cooling response to heating of the white dwarf by boundary layer irradiation, compression and shear mixing in consequence of dwarf nova outburst events, evidence of accretion belts, white dwarf masses (independent of disk emission line velocities), long term CV evolution, the white dwarf as the potential well for dwarf nova outbursts, their role as the source of thermonuclear outbursts, constraints on the disk contribution to the far *UV*, and insights on the nature of the boundary layer near the white dwarf surface. This work is being augmented by Sion's theoretical studies of white dwarf heating due to compression and downward boundary layer irradiation. In an enlarged exploration of parameter space, Sion continues to use his 1-D quasi-static code with time-variable accretion to study the heating of white dwarfs in dwarf novae and nova-like variables.

6.11.3 Studies of Dwarf Novae During Quiescence

Villanova astronomy undergraduates Kelly Lyons, Michael Dulude, Joel Urban, Colleen Henry and Ira Nadalin, working with Sion, analyzed HST archival and IUE NEWSIPS archival SWP spectra of many dwarf novae obtained when AAVSO light curve data indicated the occurrence of dwarf nova quiescence. They computed synthetic, high gravity spectra in LTE with solar composition using the codes TLUSTY195 and SYNSPEC42 and carried out fits of these models to the far *UV* continuum and narrow absorption line spectra. For CM Del, they found that the far *UV* spectrum is dominated by a hot ($T_{eff} = 22,000$ K, $\log g = 8$) white dwarf with subsolar Si abundance and all other observed metal transitions at essentially their solar values. For AH Her, they found evidence for a hot white dwarf with $T_{eff} = 27,000$ K, $\log g = 8$ and subsolar Si abundances. An HST spectrum (GHRS G160M) of AH Her reveals blue-asymmetric SiIV profiles if, due to wind outflow, they derive a single-scattering upper limit mass loss rate of $10^{-9} M_{\odot}/\text{yr}^{-1}$. Synthetic profile fits to 12 coadded HST medium resolution G160M spectra of the Si IV (1393Å, 1402Å) resonance doublet of CM Del yielded a white dwarf rotational velocity estimate of $v \sin i = 400_{-30}^{+70} \text{ km s}^{-1}$, $T_{wd} = 27,000\text{K} \pm 1000\text{K}$ and $\text{Si}/\text{H} = 1_{-0.3}^{+0.5}$ times solar.

They also carried out a synthetic spectral analysis of 5 IUE NEWSIPS archival spectra of the peculiar, very active dwarf nova CN Orionis taken at the system's lowest flux levels during quiescence. AAVSO data indicate the visual magnitude $V \sim 14$ for CN Ori at this time. On the assumption that the white dwarf contributes significantly to the far *UV* light of the system, they computed a two-parameter grid of synthetic, high gravity spectra in LTE with solar composition using TLUSTY195 and SYNSPEC42, and carried out fits of these pure photospheric models to the far *UV* continuum and narrow absorption line spectra. They found that the far *UV* spectrum in quiescence is well represented by a

hot ($T_{eff} = 30,000$ K, $\log g = 7$) white dwarf with probable subsolar silicon abundance and all other observed metal transitions at essentially their solar values. For comparison, they fitted optically thick accretion disk models to the same spectra for $M_{wd} = 0.80 M_{\odot}$ and disk inclination angle $i = 60^{\circ}$ for accretion rates $\dot{M} = 10^{-10.5}$ and $10^{-9.5} M_{\odot} \text{ yr}^{-1}$. They compared the T_{eff} of CN Ori, one of a handful of dwarf novae above the period gap, with a model photospheric analysis, to all other dwarf novae with white dwarfs of known T_{eff} derived using similar analyses. They found evidence that the white dwarfs in dwarf novae above the period gap are hotter than the ones below the gap. This trend suggests more heated, younger degenerates above the gap, and is consistent with the overall empirical evidence that mass transfer rates in dwarf novae above the period gap are higher than mass transfer rates in systems below the gap.

Ira Nadalin studied TY Piscium, a faint dwarf nova of the SU UMa subtype (systems which exhibit superoutbursts in addition to normal outbursts). During the quiescence of TY Psc, its visual magnitude is 17 while in outburst it is normally at 12th magnitude. Its orbital period is 0.08 days and it exhibits quasi-periodic oscillations (QPOs). The faintness of TY Psc during quiescence made it a marginal target for IUE observations. Remarkably, a single IUE SWP spectrum was obtained with sufficient signal to noise to carry out a model atmosphere/accretion disk analysis.

Colleen Henry studied the white dwarf in the VW Vulpeculae system. The newly found orbital period of this system is 0.16870 ± 0.00007 days or 4.05 hours and this is consistent with the observed presence of standstills and supports the idea that UZ Ser is a U Geminorum type system. The inclination angle of the system is known to be $44 \pm 12^{\circ}$, the mass of the white dwarf is $0.24 \pm 0.06 M_{\odot}$, and the system appears to have an outburst period of 30 days. Using a model atmosphere synthetic spectral analysis of VW Vul during its quiescence, she has determined the surface gravity and T_{eff} , as well as chemical abundances and an estimate of the accretion rate of the white dwarf during dwarf nova quiescence.

6.11.4 The Eclipsing Dwarf Nova OY Car

Sion, with F. Cheng, K. Horne (U.St. Andrews), T. Marsh (U. Southampton) and I. Hubeny (NASA GSFC), studied the accretion disk evolution and heating of the white dwarf in OY Car. Of the five brightest eclipsing dwarf novae (HT Cas, V2051 Oph, IP Peg, OY Car, Z Cha and HS1804 + 6753), only the last four have frequent outbursts, and of these OY Car, which has the smallest mass ratio $q = M_1/M_2 = 0.1$, shows the clearest separation between the white dwarf and bright spot. *HST* observations of the eclipsing dwarf nova OY Car after an April superoutburst are used to isolate ultraviolet spectra (1150–2500Å at 9.2Å FWHM resolution) of the white dwarf, the accretion disk, and the bright spot. The white dwarf spectra have a Stark-broadened photospheric Ly α absorption feature, but are veiled by a forest of absorption features that we attribute to absorption by intervening disk material (a *curtain*). All of the spectral fits required supersonic turbulence in the curtain material with Mach numbers of 6 to 8. All curtain temperatures were be-

tween 10,000 K and 11,000 K. There was a curtain temperature increase ~ 3 months after the superoutburst. They found that the white dwarf temperature changed from 19,700 K just 27 days after the end of the superoutburst to 18,000 K roughly 3 months after the superoutburst; the exponential (e-folding) decay time of the white dwarf temperature was 66 days. We present evidence that the heating of the white dwarf was more extensive during the superoutburst than the normal outburst. The thermal response of the OY Car white dwarf to outburst heating was compared with WZ Sagittae, VW Hydri (the most similar dwarf nova to OY Car) and with the cooling timescales of other dwarf novae after superoutburst. The measured cooling timescales of the five systems with superoutbursts appear to be shorter, the longer the orbital period (accretion rate). They found evidence of a disk flux variation, independent of the effect of white dwarf cooling, which suggests a possible contradiction of the disk instability model. To establish this however, data is required throughout a quiescent cycle.

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