Joint Institute for Laboratory Astrophysics of the National Bureau of Standards and the University of Colorado
Boulder, Colorado 80309

The Joint Institute for Laboratory Astrophysics functions as a cooperative scientific venture of the National Bureau of Standards and the University of Colorado. Housed on the University of Colorado campus, JILA draws its scientific staff from the two parent organizations. Research is conducted at JILA in a number of areas of astrophysics and atomic and molecular physics: stellar astronomy; stellar atmospheres and radiative transfer; stellar interiors; solar system physics; the interstellar medium; high energy astrophysics; extragalactic astronomy; atomic and molecular collisions, both theoretical and experimental; spectroscopy and line broadening; optical resonance phenomena; laser physics; and precision measurements.

I. PERSONNEL

In addition to the permanent scientific staff of JILA, eleven Visiting Fellows were in residence during the academic year 1978–79. They were Dr. Lloyd Armstrong, Jr., The Johns Hopkins University; Dr. Kris Davidson, University of Minnesota; Dr. Jacob Katriel, Technion-Israel Institute of Technology, Haifa, Israel; Dr. Bryan Kohler, Wesleyan University; Dr. Marc Levenson, University of Southern California; Dr. Robert T. McIver, University of California at Irvine; Dr. Leonard Rosenberg, New York University; Dr. S. David Rosner, University of Western Ontario, London, Ontario; Dr. George Anthony Victor, Center for Astrophysics, Cambridge, Massachusetts; Dr. George Wallerstein, University of Washington; and Dr. J. Craig Wheeler, University of Texas, Austin.

Postdoctoral Research Associates at JILA during the year included: Dr. Tom Ayres, Center for Astrophysics, Cambridge, Massachusetts; Steven Baughcum, Harvard University; Dr. Keith Burnett, Clarendon Laboratory, Oxford, England; Dr. Rosanna Camilloni, University of Rome; Dr. Randall Christensen, University of Illinois, Urbana; Dr. Reed Corderman, California Institute of Technology; Dr. John Eaves, University of Wisconsin, Madison; Dr. Bernhard Haisch-Eakin, University of Wisconsin, Madison; Dr. Craig Jensen, Massachusetts Institute of Technology; Dr. George M. Keiser, Duke University; Dr. Randall E. Kennerly, Indiana University; Dr. Brooke Koffend, Massachusetts Institute of Technology; Dr. Frank Kowalski, Stanford University; Dr. Steven H. Langer, Stanford University; Dr. Siu Au Lee, Stanford University; Dr. John Magyar, University of Colorado; Dr. David Nitz, Rice University; Dr. Leanne Pitchford, University of Texas, Dallas; Dr. Anil K. Pradhan, University College London; Dr. Hideyuki Saio, Tohoku University, Sendai, Japan; Dr. Gary Schmid, University of Arizona; Dr. Randall Shirts, Harvard University; Dr. Lee Schumann, New York University; Dr. J. Michael Shull, University of California at Berkeley; Dr. Theodore Simon, University of Hawaii; Dr. Charles H. Skinner, Harvard University; Dr. Arlee Smith, University of Michigan; Dr. Giovanni Stefani, University of Rome; Dr. Michael P. Strand, University of Chicago; Dr. Kenneth T.A. Taylor, Queen’s University, Belfast; Dr. Kinoshita Tachibana, Kyoto University, Japan; Dr. David van Baak, Harvard University; Dr. David Wildman, Massachusetts Institute of Technology.

Dr. John Carlsten and Dr. Jean Latour were Senior Post-doctoral Research Associates. Others who worked at JILA during the year include Dr. Veronica Bierbaum, Dr. Barney Ellison, Dr. Catharine Garmany and Dr. Earl Mosburg, and for shorter periods, Dr. W.A. Baan, Dr. Karel van der Hucht, Dr. Douglas Larden, Ms. E.M. Leep, Dr. John Rumble, Dr. Michael J. Seaton and Dr. Stephen Simpson.

Thirty-two graduate students were working toward their Ph.D.’s during 1978–79 and six completed their degrees during this period. Of these, three wrote theses on topics of interest to astrophysicists.

David Hathaway did his thesis on “Convection in rotating layers with thermal winds and application to Jupiter.” He is working with the National Center for Atmospheric Research in Boulder, Colorado.

Gibor Basri’s topic was “Supergiant chromospheres.” He has taken a position at the Space Sciences Laboratory, University of California at Berkeley.

Richard London wrote his thesis on “Astrophysical gas flows with radiative energy transfer,” and is now at the Center for Astrophysics, Cambridge, Massachusetts.

Dr. Shull has been appointed as Assistant Professor in the Department of Astro-Geophysics at the University of Colorado, and will continue as a Member of JILA.

Effective July 1, 1979 all astronomical academic activities previously under the auspices of the University of Colorado Department of Physics and Astrophysics were transferred to the Department of Astro-Geophysics, and the former department was renamed Department of Physics. The academic affiliation of five JILA Fellows (J.J. Castor, J.P. Cox, C.J. Hansen, L. Oster and R. McCray) were transferred from Physics to Astro-Geophysics. One JILA Fellow (R.H. Garstang) will have appointments in both Departments. In addition, R.H. Garstang will serve as the Director of the Division of Physics and Astro-Geophysics of the College of Arts and Sciences of the University.

II. RESEARCH ACTIVITY

Because the range of interdisciplinary effort in JILA is too broad to describe in full detail here, only work of direct interest to astronomers will be reported. Other activities primarily in atomic and molecular physics, which strengthen the overall JILA program, are referred to in Sec. III where the year’s publications are listed.

A. General topics

The monograph, Theory of Stellar Pulsation, by J.P. Cox, was completed in October, 1978. Publication, by the Princeton University Press, will occur in early 1980. Partial updating to July 1979 was effected.

Cox consulted with the T-DOT and J-15 groups at the Los Alamos Scientific Laboratory in July 1979. This visit was mostly concerned with general questions of stellar variability and related items. An invited review paper by Cox on recent results in stellar pulsation theory has been published. Similarly, an invited review paper on white dwarf oscillations was prepared by C.J. Hansen for the March 1979 workshop in Tucson, Arizona.

J. Castor, P. Conti, and R. McCray participated in the

R.H. Garstang gave an invited paper on atomic spectra in high magnetic fields at the I.A.U. Commission 14 meeting in Montreal in August 1979. He also gave an invited review on recent progress in the calculation of atomic transition probabilities at the National Research Council Symposium on Atomic Spectroscopy held at Tucson in September 1979.

T. Snow and J.L. Linsky have written a chapter on "Ultra-violet Astronomy of the Outer Layers of Stars," which will appear in Physics and Astrophysics from Spacelab (Reidel). Linsky wrote a review of "Stellar Chromospheres and Coronae" as a portion of the Report of Commission 36 to be published in the Transactions of the IAU.

Jeffrey Linsky was on the Organizing Committee of IAU Colloquium No. 51 on "Turbulence in Stellar Atmospheres" held at the University of Western Ontario on August 27-30, 1979. He is an editor of the Colloquium proceedings to be published by Springer-Verlag, which will include his review paper on "Stellar Chromospheres." At the Montreal IAU Meeting he presented a review paper on the chromospheres of RS CVn-type binaries, active single stars, and the Sun at a Joint Meeting on "Close Binaries and Stellar Activity."

Linsky is a member of the High Resolution Spectrograph Investigation Definition team and a co-investigator on the HRS experiment to fly on Space Telescope. He was also a member of the IUE Users Committee and a Guest Observer on IUE, Copernicus, HEAO-1, and HEAO-2. He is a member of the Solar Physics Working Group of the Astronomy Survey Committee.

B. Stellar Astronomy

P. Conti's group has been attacking the problem of the evolution of O-type stars and their connection with the Wolf-Rayet stars. Some of the specific issues on which progress has been made include the mass loss rate of these stars and the factors which determine it, the binary frequency and the distribution of mass ratios among the O-stars, and the frequency of WR binaries.

The most important new result for the O-type stars is that the mass loss rate of main sequence stars is not directly related to luminosity, an assumption which has been an important pillar in many recent calculations of stellar evolution including mass loss. Conti and C.D. Garmann have derived mass loss rates for several O-type stars from data obtained on the International Ultraviolet Explorer (IUE) satellite and high resolution camera. Until now, nearly all of the O- or B-type stars for which mass loss rates have been determined have been supergiants or Of stars. Although these data have been used to attempt to relate the mass loss rate of a star to its luminosity this connection is rather a consequence of the fact that optical, IR and radio emission detection methods can be successful only for those stars with the highest mass loss rates.

The new IUE observations include four OV and two early type O(f) stars. The resonance lines of C IV at 1548,1550, N V at 1239,1243 and sometimes Si IV at 1394,1403 have P Cygni profiles which are unequivocal evidence of mass loss. The mass loss rate can be computed from a comparison with theoretical profiles computed by Castor and Lamers, and the rates derived indicate a very substantial difference in mass loss rates among stars of the same bolometric magnitude. An HR diagram of the upper part of the main sequence based partly on those data (Conti and McCray) suggests that only stars initially more massive than \(\sim 40.\) \(\dot{M}\) have substantial (\(\geq 10^{-6}\) \(\dot{M}\)) mass loss rates. Those stars more massive than this, but near the ZAMS (e.g., HD 93250 and 9 Sgr), do not have such large rates; the wind appears to increase dramatically soon after the star leaves the ZAMS but while it is still a main sequence star, i.e., burning hydrogen in the core. We frankly do not understand this result. Although it is clear that line radiation forces are important to determining the wind velocity law, there is apparently another physical mechanism which has not yet been accounted for in the stellar wind theory.

As part of a program on O-type binaries, P. Massey has analyzed the double line systems HD 149404 and HD 48099. Work on other systems is proceeding, including HD 150136, a double line system, and several single line systems. Garmann, Conti and Massey have completed a study of the binary frequency of all O-stars brighter than magnitude 7. The results show that only 40% of the O-stars have binary companions, and furthermore, the mass ratios of the binaries are all greater than 0.3.

During the past year, Conti has obtained image tube spectrograms at the 4 m telescopes at Kitt Peak and Cerro Tololo of over 100 known galactic WR stars, about 40 in the LMC, and 6 of the 8 in the SMC. This collection of data has led to an unexpected result: the fraction of WR binaries is about 36% in the galaxy, 40% in the LMC and 100% in the SMC. Previous surveys of galactic WR stars had used a much smaller statistical sample and obtained much higher fractions of binaries. As indicated by the LMC stars, the intrinsically brighter WR stars are preferentially binaries since the companion dominates the continuum; the fainter WR stars are preferentially single. The possibility of single WR stars is now established statistically, and if all the systems with absorption lines are not binaries, then the percentage of binaries may be even smaller. Massey is studying the absorption line systems to get new orbits and has found at least one system to be single. P. Conti and R. McCray have written a paper entitled "Strong Stellar Winds," to be published in Science, in which they review the observations and theoretical implications of the stellar winds of hot stars.

L. Oster, in collaboration with W.J. Altenhoff (Max-Planck-Institut fuer Radioastronomie) and H.J. Wendker (Hamburger Sternwarte), discussed the spectrum of the steady radio emission of Betelgeuse with the result that there appear to be two components, one consisting of black-body radiation from the stellar disc, the other of emission from some form of extended chromosphere.

Linsky, S.P. Worden (Sacramento Peak Observatory), W. McClintock (LASP), and R.M. Robertson have reported on their systematic study of the Ca II H and K lines using the KPNO 4-m echelle spectrograph. They obtained high resolution, absolute flux profiles of these lines in 43 stars of spectral types F0-M2, and from the data estimated chromospheric radiative loss rates. They also discussed line asymmetries, chromospheric radiative loss rates in the He line, and compared line widths to the scaling laws proposed by Ayres.

Linsky, D.M. Hunten (KPNO), R. Sowell (KPNO), D.L. Glackin, and W.L. Kelch have reported on their systematic study of the Ca II \(\lambda 8542\) line using the KPNO McMath tele-
scope and an SIT camera. They obtained high resolution profiles of this line in 49 stars of spectral type F9-K3, and from the data determined chromospheric radiative loss rates. While they find no stars with resolved double emission features, they do find evidence that the $\lambda$ 8542 cores of active chromosphere stars are filled in, and that these stars have large chromospheric radiative loss rates in the $\lambda$ 8542 line.

Using the International Ultraviolet Explorer (IUE) spacecraft G.S. Basri and Linsky have obtained high resolution, absolute flux profiles of the Mg II resonance line profile in 15 stars of spectral type G2-M2. They also estimate chromospheric radiative loss rates in these lines and compare these rates to corresponding rates for the H and K lines and the Ca II $\lambda$ 8542 line. They find that the ratio of Mg II surface flux to total surface flux is independent of stellar luminosity and thus gravity, contrary to theoretical predictions, and may decrease slowly with decreasing effective temperature. The factor of 10 range in this ratio at each effective temperature may be due to differences in the fractional surface area covered by plages.

T.R. Ayres and Linsky have obtained and analyzed IUE spectra of $\alpha$ Cen A, $\alpha$ Cen B, and Capella. They find that $\alpha$ Cen A and $\alpha$ Cen B are very similar to the quiet Sun, with similar surface fluxes of chromospheric and transition region lines and deduced transition region pressures. From high resolution spectra of Capella taken at maximum and zero velocity separation, they were able to conclude that most of the observed emission is from Capella B, the F9 III rapidly rotating secondary star. Capella B has properties similar to RS CVn-type systems, presumably due to its rapid rotation and probable large magnetic field which is strengthened by rapid rotation.

T. Simon and Linsky are computing chromospheric models for the RS CVn systems HR 1099 and UX Ari, and they are analyzing the 1/1/79 flare on UX Ari observed by IUE.

M. Giampapa (Arizona), T.J. Schneeberger (Sacramento Peak Observatory), S.P. Worden (SPO), Linsky, and W. McClintock (LASP) have been studying dMe flare stars by the technique of time-trailed spectroscopy with the 4 m echelle at KPNO and simultaneous photometry. In the quietest spectrum of AD Leo, they find that the He I lines are collisionally excited rather than formed by recombination following photoionization. Their analysis of the flare spectrum on AD Leo is that dMe star flares are hotter and denser than their solar counterparts. This program is continuing with simultaneous IUE time-trailed spectroscopy.

Several programs have been completed to search for coronae in late-type stars using HEAO-1. This work involves T.R. Ayres, Linsky, and collaborators at Berkeley and Cal. Tech. They have discussed X-ray emission from the 40 Eri system, BY Dra, AD Leo, $\gamma$ Ori, 70 Oph, and HR 6806. They conclude that the singlet or widely-separated binary late-type stars with the strongest X-ray emission are characterized by the luminosity ratio $L_x/L_{bol} = 10^{-6}$, similar to a solar plage. This work is continuing with HEAO-2.

S.M. Kahn (Berkeley), Linsky, K.O. Mason (Berkeley), Haisch, C.S. Bowyer (Berkeley), N.E. White and S.H. Pravdo (NASA Goddard) have analyzed the X-ray fluxes and spectra of two flares each on AT Mic and AD Leo observed by HEAO-1. For a very large flare on AT Mic, they determine a temperature of $3 \times 10^7$ K and emission measure of $1.4 \times 10^{54}$. The estimated $L_x/L_{bol}$ ratios exceed unity, which is inconsistent with Mullan’s flare model.

Using HEAO-2, Haisch and Linsky have measured the quiescent coronal temperature and emission measure of the flare star Proxima Centauri. In a major collaborative program to monitor Prox Cen with HEAO-2, IUE, the Parkes radio telescope, and optical telescopes, they detected an X-ray flare with no UV, optical, or radio component. This flare was characterized by a temperature of $17 \times 10^7$ K during the rise phase and $12 \times 10^7$ K and larger emission measure during the decay phase.

Ayres examined preliminary HEAO-1 detections of cool stars and concluded that stellar rotation must play an important role in controlling the mean strength of coronal soft X-ray emission in convective stars. For example, close binary systems in which the two components are locked into rapid rotation by tidally-enforced synchronism, and evolutionarily young, rapidly rotating cool stars such as Capella B, tend to have large X-ray-to-bolometric luminosity ratios, whereas old, slow rotating field stars, such as $\alpha$ Centauri A and B, and the Sun itself, tend to be weak soft-X-ray sources. The rotation-activity connection seen in X-rays parallels similar trends seen in Ca II emission by Kraft, Skumanich and others.

G. Wallerstein continued work on the spectra of the components of the visual binary MWC 349. The brighter star shows numerous permitted and forbidden lines in emission superposed on a weak continuum. The fainter star shows emission only at Hz, and a continuum which is strong in the red. This continuum, together with the many weak emission lines from the primary, probably explains the observations previously ascribed to a preplanetary disc. Wallerstein and E.W. Brugel (University of Wisconsin) determined the radius and absolute magnitude of the Population II cepheid XX Virginis from a radial velocity curve. The absolute magnitude is $-0.7$. Wallerstein has also obtained new radial velocity curves for $\delta$ Cephei. The amplitude of the Hz curve is 15 km sec$^{-1}$ larger than the amplitude for metallic lines, suggesting that the Hz absorption is formed high in the atmosphere of $\delta$ Cep.

C. Stellar atmospheres and radiative transfer

J. Castor and H.J.G.L.M. Lamers have published an atlas of spectral line profiles for resonance lines formed in rapidly expanding stellar envelopes (P Cygni lines). These profiles allow an observer of such a line to estimate the column density of absorbing ions.

M. Seaton, J. Castor, and J. Lutz (Washington State University) have completed an analysis of the spectrum of the central star of the planetary nebula NGC 6543 observed with the IUE satellite. The rate of mass loss for the central star is quite large, proportionately as large in comparison with the stellar luminosity as for the Wolf–Rayet stars.

D. Friend is working with J. Castor on including the effects of stellar rotation and overlapping resonance lines in the mechanism of radiatively-driven stellar winds.

J. Powelson and J. Castor are modeling the excitation and ionization of Fe II in the nuclei of type 1 Seyfert galaxies using a multi-level analysis including collisions, fluorescence, self-absorption, and charge exchange between Fe$^{+}$ and H$^0$. They hope to find a definitive answer to the question of the mechanism that excites the observed permitted emission lines of Fe II.

D. Van Blerkom (University of Massachusetts) and J. Castor have completed an analysis of the Hz line in the OF star $\zeta$ Puppis, leading to a value for the mass-loss rate and a determination of the run of velocity.

D. Hummer and M. Barlow have been studying O VI lines in the spectra of very hot stars. O VII has been detected in at least
one object. Hummer has been extending the Sobolev method and has been improving its computational aspects.

R. London, R. McCray and L. Auer (High Altitude Observatory) have investigated the structure of a stellar atmosphere illuminated by a companion binary X-ray source, such as the Her X-1-HZ Her system. They have solved the non-LTE radiative transfer equations using the complete linearization method of Auer and Mihalas. They find that cooling due to line emission does not substantially modify the atmospheric structure. Their results for the pressure at which the stellar atmosphere becomes thermally unstable and their estimate of the atmospheric mass loss rate caused by X-ray heating agree fairly well with those obtained by L. Anderson.

Linsky and his collaborators are continuing their program of computing model chromospheres, using partial redistribution diagnostics, to match absolute flux profiles of the Ca II and Mg II resonance lines. W.L. Kelch, Linsky, and S.P. Worden (Sacramento Peak Observatory) have derived models for eight main sequence stars of spectral type F0-M0 with a range of chromospheric activity. They find that the more active chromosphere stars generally have steeper temperature gradients in their lower chromospheres, the temperature minima are located at larger values of the mass column density, and in some cases the temperature minima are appreciably hotter than for quiet chromosphere stars. They also find that Hz is computed to be in emission in the dK7e star EQ Vir and in absorption in the dM0 star 61 Cyg B, consistent with observations, using models computed to match the Ca II lines. Thus the difference between dM and dMe star chromospheres may be simply explained by steeper chromospheric temperature gradients in dMe stars, presumably due to enhanced nonradia-

G.S. Basri and J.L. Linsky have computed chromospheric models for the supergiants β Dra, ε Gem, and α Ori matching observations of the Ca II and Mg II resonance lines observed by IUE. T. Simon, W.L. Kelch, and Linsky have developed codes to model the bright C II, Si II, and Si III lines observable by the IUE short wavelength spectrograph, and have computed a chromospheric model extending up to 30,000 K for ε Eri using IUE observations.

Linsky and B.M. Haisch have obtained IUE short wavelength spectra of 20 G-M stars which show a qualitative separation into two groups. The “transition region” group contains emission lines representative of 5–10,000 K plasma, similar to the solar chromosphere, and 20,000–200,000 K plasma similar to the solar transition region. The “nontransition region” group contains chromosphere lines but no transition region lines, indicating the absence or low amount of plasma at temperatures in the 20,000–200,000 K range. In analogy with the Sun, the “transition region” group stars presumably have hot coronae. J.M. Pasachoff (Williams College), Linsky, Haisch, and A. Bogess (NASA Goddard) have reported on this result and described the observations of IUE in a Sky and Telescope article.

Haisch, Linsky, and G.S. Basri proposed that the “nontransition region” stars have cool winds in which Lz radiation pressure initiates a supersonic flow, but smoother mechanism (perhaps Alven wave pressure) is needed to maintain the flow in this cool wind.

Ayres has discussed scaling laws for the thickness and mean electron density of late-type stellar chromospheres. These scaling laws lead to predictions of the widths of the K1 minimum features, K2 peak features, and FWHM of the Ca II K line emission core, as well as analogous features in the Mg II resonance lines, as functions of the stellar gravity and chromospheric nonradiative heating rate. These relations simply account for the empirical Wilson–Bappu relation.

D. Stellar Interiors

J.P. Cox investigated the effect of radiation pressure on an instability strip resulting from an envelope ionization mechanism. The results have now been published by Cox and R.F. Stellingwerf (Rutgers University). The effect of radiation pressure (in only fairly modest amounts) is found to cause the slope of an instability strip to have the same sign as the main sequence. A possible envelope ionization mechanism has been suggested by Stellingwerf (the “bump” mechanism, 1979 Ap. J. 227, 935). These considerations appear somewhat promising when applied to the β Cephei variables, whose excitation mechanism has not yet been satisfactorily explained. Some conjectures regarding these stars have been offered by H. Saio and Cox, and will appear in the proceedings of the recent workshop held at Tucson, Arizona.

The problem of the linear, nonradial, nonadiabatic oscillations of spherical stars was solved by Saio by treating the system as six first order complex differential equations in six Dziembowski-like variables. Such a calculation has been applied to slightly evolved models of 7, 12, and 20 solar masses, which evolve through the parts of the Hertzsprung–Russell diagram occupied by the β Cephei variables. The main purpose of this work was to determine how effective the Stellingwerf bump mechanism would be in exciting nonradial oscillations. It appears that, for those models for which a test is possible, the bump mechanism will excite certain nonradial oscillations about as effectively as radial oscillations. The first results of such a calculation were presented at the workshop referred to above in Tucson, Arizona.

It has been suggested by J.C. Wheeler [Astrophys. J. 225, 212 (1978)] that the R Coronae Borealis stars might be among the progenitors of Type I supernovae. In part to test Wheeler’s suggestion, and also because of the intrinsic interest of these very luminous stars, we have begun a theoretical investigation of the pulsation properties of the R CrB stars. Because of their relatively large luminosities and small masses, their pulsations are very nonadiabatic. This feature leads to some interesting and somewhat novel results.

Saio and Wheeler have devoted a fair amount of time to studying some of the effects of interior mixing on stellar evolutionary tracks. The extent of the mixing is being treated as a parameter. The effect of a possible nonthermal contribution to the pressure associated with the mixing is also considered. Comparison of the theoretical isochrones with the H–R diagram of the open cluster NGC 7789 seems to suggest that most of the blue stragglers in the cluster may be explained by the models with partial mixing in the interior.

Saio has also investigated the stability of the solar interior against mixing, taking into account recent models and also the carbon-nitrogen-oxygen cycle. His conclusion that the solar material is stable against mixing agrees with earlier work on the problem ([e.g., Rosenbluth and Bahcall, Astrophys. J. 184, 9 (1973)].

Considerable time was spent by Cox, working with M.L. Aizenman (National Science Foundation) on the “r modes” of rotating stars (Papaloizou and Pringle 1978 M.N.R.A.S. 182, 423).

B.W. Carroll has been investigating the effect of slow rotation on the nonadiabatic eigenfunctions and eigenvalues of
nonradial stellar oscillations, using Saio's program for calculating nonradial oscillations nonadiabatically. Carroll also performed some calculations on a mode classification scheme devised by Gabriel and Scuflaire. Carroll also assisted Cox in the preparation of the manuscript of Theory of Stellar Pulsation.

The thermonuclear reaction rates program, started some seven years ago by the University of Colorado Nuclear Physics Laboratory in collaboration with C.J. Hansen, has resulted in firm rates for 72 proton induced reactions on nuclei with Z ranging from 5 to 62. The temperature range covered is $1 \leq T \leq 7$. A final report will be published in Atomic Data and Nuclear Data Tables. Helium induced reactions are still under study and about 20 have been completed to date.

An investigation of the oscillatory properties of white dwarfs with crystalline cores has been carried out by Hansen and H.M. Van Horn (University of Rochester). This study showed that g-mode oscillation frequencies were driven to larger values (shorter periods) for models with extensive crystalline cores.

A brief study of the location of the ZZ Ceti stars on the Hertzsprung–Russell diagram has been carried out by Cox and Hansen, and the results were reported at the Rochester IAU Colloquium No. 53. The main conclusion of this study is that the driving mechanism for the several hundred second observed oscillations of these stars should be located at about $(1-2) \times 10^5 K$, roughly the temperature at which the Stellingwerf bump mechanism should be operative. Detailed calculations of W Dziembowski showed instability at these periods due to the bump mechanism.

Hansen and D.F. Cioffi have completed an analysis of the torsional oscillation modes of neutron star crusts. Using realistic models, they find that, for models with gravitational masses exceeding some 0.6 solar masses, the periods of oscillation fall into two classes. Those related to the fundamental mode have periods of about 20 msec whereas higher harmonics generally have periods near 1 msec. They suggest the possibility that the 20 msec oscillations could be associated with pulsar subhypes whereas the higher harmonics might give rise to observed micropulses.

Nonadiabatic analyses of the stability of nonradial g’ modes in 1 solar mass models is in progress by Saio. The influence of the perturbation of convective flux on stability might be important. He is trying to include the effect of coupling between pulsation and convection in these analyses.

E. Solar system physics

L. November, K.B. Gebbie, and J. Toomre, in collaboration with G.W. Simon (Sacramento Peak Observatory), have detected a new scale of convective motion in the solar photosphere and chromosphere. Time averaged Doppler measurements made at disk center with the SPO diode array instrument show strong evidence for cellular motion on a scale of 7–10 Mm, intermediate between granulation and supergranulation. These structures, or “mesogranules,” correlate well between a photosphere Fe I line and a Mg I line formed just above the temperature minimum. Many of them persist over several 30 min averaging periods. Further, simultaneous observations carried out in a Si II line using the University of Colorado ultraviolet spectrometer on the OSO-8 satellite reveal that such scales of persistent flow are also present in the middle chromosphere.

B. Mihalas and J. Toomre have been studying the propagation of internal gravity waves in the solar atmosphere. The results from linearized but nonadiabatic calculations are used to determine the energy transport by these waves, to estimate the effects of H cooling in the low photosphere, and to predict nonlinear wave breaking heights with associated production of turbulence and local heating of the atmosphere. The work concludes that a significant flux of internal gravity waves may be present in the middle chromosphere and contribute to heating there. Further, these waves would be difficult to detect, for they would broaden some spectral lines or produce asymmetries, but would not Doppler shift most lines significantly.

D. Hathaway, J. Toomre, and P. Gilman (HAO) have attempted to provide dynamical explanations for the observed axisymmetric cloud bands of Jupiter. Based on linearized stability analysis, they conclude that east-west oriented convection rolls are indeed the most unstable, and thus presumably the preferred ones, provided that a significant horizontal temperature gradient is present. The vertical temperature gradient is taken to be superadiabatic and effects of rotation are important. These convection rolls would extend down to a depth of about 15,000 km, or to about where hydrogen becomes metallic, in order to obtain the observed widths for the cloud bands.

J. Latour and J. Toomre, in collaboration with J.-P. Zahn (Nice), have continued their study of compressible convection in A-type stars using the anelastic modal equations. The large-scale flows, much like supergranulation, driven in the deeper helium convection zone are able to penetrate upward into the hydrogen convection zone. The effects of pressure forces there are to brake these motions, thereby turning them into strong horizontal shear flows. Thus the shallow but highly unstable hydrogen zone can largely prevent supergranular scale motions from getting through into the atmosphere with any significant portion of their original momentum. The deflection of the large-scale flows is partly a response to the rapidly decreasing scale height. If these results carry over to the solar convection zone, then an explanation may exist for why the observed velocity amplitudes in supergranular flows in the atmosphere are so small. This work also suggest that strong horizontal flows related to supergranulation and giant cells may be present just below the solar surface.

J. Hart, J. Toomre, P. Gilman (HAO) and G. Fichtl (MSFC) have a convection experiment now approved for flight on the Shuttle-launched Spacelabs 1 and 3. The coupling of convection with rotation will be studied in spherical shells of fluid under a simulated radial gravity field, the latter achieved by an electric field potential and suitable working fluids. In addition to a radial temperature gradient, pole to equator temperature differences can also be imposed. The goal is to examine the preferred forms for convection in spherical geometries when rotation effects are significant, with both Jupiter and the Sun in mind. Though highly simplified, these experiments will explore convection cell shapes and orientations, induced differential rotation, and heat fluxes over a wide parameter range in which nonlinear effects are dominant.

K. Gebbie, W. Kint, L. November, and J. Porter, in collaboration with J. Davis (NRL), are studying the formation of the helium resonance lines in the prominent solar flare of 15 June 1973. NRL/Skylab photgraphic images have been reduced and analyzed to produce digital composite maps of the He I and He II line ratios during the evolution of the flare. These are to be compared with solutions for the transfer of helium line radiation in simplified dynamical models of the flare plasma.

G.S. Basri, J.L. Links, with J.D.F. Bartoe, G. Brueckner and M.E. Van Hooseier (all of the NRL), have analyzed NRL rocket spectra of the core and wings of the Lz line in active and
quiet regions of the solar atmosphere using partial redistribution diagnostics which explicitly include a frequency-dependent redistribution term due to electron and ion Stark broadening. They find that the core and wings of Lz exhibit weak limb brightening, consistent with their calculations, and that line asymmetries can be interpreted in terms of downflows in the network and outflows in holes. They present a new model for the mean quiet Sun and models for dark points in cells, bright points in the network, and for a bright plage.

Ayres, in collaboration with L. Testerman (KPNO), has obtained extensive spectra of the 2.4 μm and 5 μm CO regions with the 1st Fourier Transform Spectrometer of the McMath Solar Telescope at Kitt Peak. These data have been reduced and Ayres is currently studying the influence of 2-D thermal inhomogeneities on the formation of the photospheric CO spectrum. His intention is to probe the temperature-pressure stratification of the cooler atmospheric components in which the molecular features are preferentially formed. In fact, the limb darkening behavior of saturated lines in the 5 μm fundamental bands of CO suggests the presence of material at temperatures as low as 3600 K in the solar outer atmosphere.

Ayres has participated in the Skylab Active Region Workshop, specializing on the question of excess radiative cooling in the plage and quiet Sun chromospheres. He constructed chromospheric radiative cooling curves based on numerical simulations of the resonance and subordinate lines in Ca II, Mg II, H I. He found that the temperature-dependent coefficient of the line cooling has roughly similar shapes in the plage and quiet Sun atmospheres although the Ca II and Mg II emission features become effectively thicker higher up in the plane owing to the enhanced electron densities. In fact, the major difference between the plage and quiet Sun cooling is the presence of systematically larger chromospheric pressures in the former.

Ayres also discussed the H⁺ cooling dichotomy. In particular, H⁺ is usually considered to be the principal radiative coolant at the base of the chromosphere, consequently H⁺ excess radiative cooling should be reliable indicator of the mechanical energy deposition thought to be required to drive the temperature inversion. In reality, however, H⁺ is a major source of heating in the solar outer atmosphere, owing to the substantial absorption of photospheric radiation by chromospheric H⁺ ions. Ayres further argues that even if the shape of the radiative cooling curve for T < 6000 K were known accurately, it would still be possible to seriously overestimate chromospheric cooling rates from conventional single-component models. If actual chromospheric cooling rates are found to be substantially less than the conventional estimates, mechanical heating may not be by acoustic waves.

Ayres and collaborators at Kitt Peak (Brault and Testerman) are currently attempting simultaneous, cospatial observations of the 0.39 μm Ca II H and K wings and the 2.4 μm CO bands with the solar FTS in a dual-detector mode. They anticipate that such observations will help to clarify the nature of the dominant thermal inhomogeneities at mid-photosphere heights, owing to the opposite temperature sensitivities of the ultraviolet resonance lines and the infrared molecular bands.

J.E. Faller, R.L. Rinker and M.A. Zumbecher continued the development of a portable absolute gravimeter.

F. Interstellar medium

D. Hummer has been investigating the consequences of the stellar wind from the nucleus of a planetary nebula interacting with the nebula itself. One purpose is to see if the anomalous Zanstra temperatures of certain nebulae are related to the stellar winds.

J.M. Shull and C.F. McKee (University of California, Berkeley) have made a theoretical study of the structure, ionization, and emission from radiating interstellar shock waves, with emphasis on the effects of ionizing UV precursors. Observationally, Shull has investigated interstellar cloud abundances and velocities towards several stars near the Orion OB association, using the Copernicus OAO-3 UV spectrometer. Similar studies for other early type stars are under way, using the International Ultraviolet Explorer. These systematic programs may elucidate the relationship between young stellar association and the dynamics and ecology of the interstellar medium.

Shull has completed a theoretical study of the effects of a supernova explosion in a dense interstellar molecular cloud. Grain cooling and reprocessing of the X-rays produced in the remnant interior result in an infrared luminosity peak at roughly the shell formation time—20 years after the explosion in a dense cloud. A related study by Shull of the dynamical effects of the stellar wind of the O-star progenitor has shown that the wind cavity will modify both the compact H II region and the dynamics of the subsequent supernova remnant.

Shull has computed the heating, ionization, and line excitation produced by X-ray photoelectrons interacting with diffuse interstellar gas of various ionization fractions. These studies are useful in assessing the effects of hard X-rays on the interstellar medium.

W. McClintock (LASP), R.C. Henry, H.W. Moos, and R.C. Anderson (Johns Hopkins University), and J.L. Linsky are continuing their program of analyzing Copernicus observations of the Lz line profiles in the nearby stars e Eri, e Ind, α Cen A, α Aur, and α CMI. They derive the range of hydrogen and deuterium column densities and line broadening parameters consistent with the data, and they conclude that the properties along the lines of sight toward these four stars are consistent with the same interstellar flow vector, a hydrogen density of 0.1 cm⁻³, and a D/H ratio of 1.8×10⁻⁴, except that the hydrogen density toward Capella is 0.04–0.05 cm⁻³. They are presently analyzing high signal-to-noise spectra of the Lz line profile toward α Cen A, obtained with IUE, to test the H and D/H results obtained from their Copernicus data.

M.J. Seaton continued his work on planetary nebulae, including work on [Ne IV] in NGC 7662 with J.H. Lutz (Washington State University).

K. Davidson, in collaboration with T.R. Gull (Goddard Space Flight Center), obtained ultraviolet spectra with the IUE satellite of the brightest filamentary condensations in the Crab Nebula with a view to carbon abundance determinations.

G. High-energy astrophysics

R. McCray, P. Boynton (University of Washington), and J.M. Shull have obtained time-resolved soft X-ray spectra of the pulsating X-ray source Her X-1, using the Einstein X-ray observatory as guest investigators.

S. Langer has investigated, by means of Monte Carlo simulations, the accuracy of the new theory for Comptonization of X-ray spectral features developed by Illarionov, Kallman, McCray and Ross [Astrophys. J. 228, 279 (1979)].

S. Langer, R. McCray, and W.A. Baan (Institute for Advanced Study) have studied the processes by which X-ray cyclotron lines are emitted in an accreting magnetized neutron star. Langer has calculated the cross sections for several exci-
tation processes in $10^{12}$–$10^{13}$ gauss magnetic fields. Using these results Langer et al. have solved a kinetic equation for the electron velocity distribution. They find that significant departures from a Maxwellian distribution occur, leading to a reduced line emission rate and a reduced Doppler width for the line.

T. Kallman and R. McCray continue to investigate models for X-ray heating and ionization of gas surrounding a cosmic X-ray source. Recent calculations include far more detailed consideration of atomic processes, including the effects of trace elements such as iron. Special attention is paid to the calculation of the optical and UV emission line spectrum, and to the effects of line cooling, including resonance line transfer and the Bowen fluorescence mechanism.

J. Castor, T. Kallman, and R. McCray are calculating theoretical models for the modification of ultraviolet P-Cygni line profiles such as C IV λ 1549 and Si IV λ 1398 due to photionization of a stellar wind by a binary X-ray source. This effect has been observed recently by A.K. Dupree et al. in the spectrum of the binary X-ray system 4U 0900–40/HD 77581.

K. Davidson and R. McCray have investigated models for the remarkable galactic object SS433, which appears to eject mass at velocity $v = 0.27 c$ in well-collimated twin beams that precess with a 164$^4$ period. They suggest that the beams are collimated by nozzle-like structures in the inner boundary of an accretion disk, and that the emission lines are caused by interaction of the matter in the beams with an ambient stellar wind.

Shull has studied the dynamical effects of stellar collisions on binary X-ray sources in the cores of globular clusters. These collisions can shrink the orbits of such binaries as well as exchange stars, with implications for the nature and lifetimes of the observed cluster X-ray sources.

**H. Extragalactic Astronomy**

L. Oster and D. Eder studied the dependence of the angular separation of double radio sources on the redshift of the parent galaxy. It was concluded that the upper-limit envelope shown by currently available data was real and reflected a change of the lifetime of the plasmons with age of the universe. The detailed comparison with theoretically developed models showed that the ambient medium must have a density that is significantly below closure density, that the life span of the plasmons is limited by synchrotron and inverse Compton losses, and that as a consequence models with in-situ resupply of relativistic electrons and multiple ejections are favored.

J. M. Shull and J. Silk (University of California, Berkeley) have modeled the UV emission from supernova remnants resulting from a burst of star formation in primeval galaxies at large redshift. Applications were made for detection of redshifted emission from these proto-galaxies and to limits on star formation set by the diffuse extragalactic background at 1500 A and 5100 A.

K. Davidson completed the analysis of digital pictures of the region around the quasar PHL 957 in an attempt to find a halo around the quasar. No hint of a halo was found, the upper limit on brightness being far less than the brightness of the night sky. This is evidence against the hypothesis that the absorption lines in the quasar spectrum are formed in clouds that have been ejected from each quasar.

A. Brillet and J.L. Hall completed an improved laser test of the isotropy of space. The result expressed as a fractional length variation is $\Delta l/l = (1.5 \pm 2.5) \times 10^{-15}$, a factor 4000 improvement over the best previous measurement.

**I. Atomic and molecular processes**

J. Cooper is studying the redistribution of radiation due to collisions, with emphasis on the scattering of light from line center into the quasi-static line wings. The original heuristic approach of Cooper [Astrophys. J. 228, 339 (1979)] has been reformulated in a rigorous manner by Burnett and Cooper. It confirms, for isolated lines, that frequency dependent line width parameters (in contrast to constant, Lorentzian, widths) have to be used and, further, that the scattering cannot be characterized, in general, by simple absorption (or emission) profiles, but more generalized line shape functions have to be defined. An experimental program is under way to test these predictions.

Redistributions of Lyman α, Lyman β (and eventually Hα) is being studied for conditions appropriate to the solar chromosphere (where natural broadening often exceeds Stark broadening). Again, constant line width parameters cannot be used throughout the profile. The effect of ions (often neglected in scattering) is found to be comparable to electrons, and the metastable 2s state forms a reservoir that plays an important role in scattering in the wings.

A. Zajonc and A. Gallagher have measured electron impact excitation cross sections for the 3s, 4s, 3d and 4d states of Li I. The s and d state cross sections show very different forms near threshold.

Extending the work of D. Hummer and D. Norcross, excitation rates are being calculated by A.K. Pradhan for transitions involving the n = 2 complex in He-like ions. It has been found that resonances in the excitation cross sections in the near threshold region enhance the overall reaction rates significantly. A detailed study is being made of such resonance effects. The ions considered are Be II, C V, O VII, Ne IX, Si XlII, Ca XIX, Fe XXV, Se XXXIII and Mo XLI.

R.H. Garstang did some further calculations of oscillator strengths for astrophysically important lines of neutral technetium. He also continued his study of possible two-photon spontaneous emission transitions which might contribute to the de-excitation of metastable levels.

S.D. Rosner, G.H. Dunn and J. Luine continued work on the study of ions confined in a Penning trap at 4 K. Attempts were made to study the reaction of C$^+$ and He$^+$ ions (Resner, W.C. Lineberger, P. Jones and R. Mead completed a study of the electronic structure of C$^+$. The observed optical absorption spectra could all be explained as transitions from high vibrational levels of the ground electronic state, these levels lying above the detachment limit. Thus single photon autodetachment was being observed.

J. Katriel, with J.M. Peak (Sandia Laboratories), has been studying the behavior of the hydrogen molecular ion in a high magnetic field. The method used takes advantage of the fact that the field-free H$_2^+$ molecule problem is exactly soluble. This guarantees high accuracy for low and intermediate fields.

R.R. Corderman, P.C. Engeling and W.C. Lineberger completed work on the laser photoelectron spectroscopy of the negative ions of iron, cobalt and nickel. The electron affinities are 0.16 eV (iron), 0.66 eV (cobalt) and 1.16 eV (nickel). Fine structure in the negative ions was measured.

G.A. Victor and C. Laughlin (University of Nottingham) calculated intercombination line oscillator strengths for the Mg I isoelectronic sequence.

D.C. Gregory, with D.H. Crandall, R.A. Phaneuf and B.E. Hasselquist (Oak Ridge National Laboratory), measured cross sections from threshold to 1500 eV for ionization of C$^+$.
N$^+$ and O$^+$ ions, and observed abrupt increases in the cross sections at electron energies associated with an inner shell excitation followed by autoionization.

K. Tachibana and A.V. Phelps measured electron excitation rate coefficients for the C$^2\Pi_u$ state of N$_2$.

The JILA Atomic Collision Cross Section Information Center published a Bibliography of Low Energy Electron and Photon Cross Section Data covering the period January 1975 to December 1977 (NBS Spec. Publ. No. 426, Suppl. 1, 1979). The Center continued to issue a Newsletter on Energy Transfer Collisions of Atoms and Molecules; this appears quarterly under the editorship of J.W. Gallagher. Several staff members collaborated with authors at three other institutions to produce a Compilation of Data Relevant to Nuclear Pumped Lasers: this compilation covers ion-atom recombinations, ion-molecule reactions and energy transfer, and other subjects.

III. PUBLICATIONS

(Coauthors not connected with JILA are shown in parentheses.)


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Horowitz, A.B., and Leone, S.R. (1978). “Laser-Excited Resonant Isotopic V-V Energy Transfer: $H^\text{35}^{17}Cl-H^\text{37}^{17}Cl$, $H^\text{35}^{19}Br-H^\text{37}^{19}Br$, D$^\text{35}^{17}Cl-D^\text{37}^{17}Cl$, and D$^\text{35}^{19}Br-D^\text{37}^{19}Br$,” J. Chem. Phys. 69, 5319–28.


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ROY H. GARSTANG