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Theoretical and Experimental Studies in
Ultraviolet Solar Physics

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INTRODUCTION

Research under the support of this Grant (NASA NGL-22-007-006) at Harvard College Observatory has advanced substantially during the past report period.

Notably, as the result of laboratory studies, by using the flash pyrolysis technique, Dr. G. Tondello has recorded, for the first time experimentally, autoionization and photoionization features in the spectrum of Fe I. His earlier work on the S I spectrum has been prepared as Scientific Report #33 (1971) and has been accepted for publication by the Astrophysical Journal.

Additional work on Fe I oscillator strengths, determined from anomalous dispersion of shock heated gases has been completed and reported as Scientific Report #34 by Drs. Huber and Parkinson. This paper has been accepted for publication in the Astrophysical Journal.

The laser and dye laser systems have continued to be used for spectroscopic studies by Drs. McIlrath, Mitchell and colleagues.

Dr. J. Kohl has continued the development of the extreme ultraviolet shock tube facility and has expanded his work on the photoionization continuum of aluminum by employing a Mach-Zehnder interferometer.

Theoretical work on a wide number of astrophysical subjects has been performed by Drs. Dupree and Withbroe.

Descriptions of the above activities will be discussed in the following under three categories: Instrumentation, Theoretical Work and Spectroscopy.

INSTRUMENTATION

Dr. J.L. Kohl has continued his development of a shock tube facility to be used in the extreme ultraviolet. Atlas Chemical Industries, Inc., were employed to design, test and supply a high power explosive squib for driving the windowless shutters and they have produced an appropriate squib capable of accelerating a 40 gram mass to a speed of 175 m/sec in 350 microseconds. The driving piston and housing which contains the squib as well as a test assembly have been designed and their construction have just been concluded. The design of the windowless test section and shutter assemblies are tentatively completed and await the results of the performance tests. The appropriate electronic devices for activating the squibs and for monitoring the shutter speed are being assembled. The windowless shock tube design is expected to provide a near-simultaneous opening to full aperture of two shock tube windows in less than 10 microseconds.

Work was continued by Mr. J. Carlsten on development of a dye laser to be used to populate selectively the triplet metastable in Ba I. DDI in DMSO was the first dye attempted, which produced a $2.5 \text{ \AA}$ wide output when tuned with a grating to the 791.1 nm intercombination line. However two problems readily became apparent. First, the output, which ran about 30 mJ with a ruby pump energy of 1J, was quite unstable from shot to shot while the average efficiency was noticed to drop by a factor of 10

during the first day after preparation. Second, when the output was high, there was evidence of damage being done to the surface of the aluminum coated replica grating which was used in the cavity to tune the output.

Several preliminary absorption spectra were taken with a Garton flash tube to see if pumping of the triplet was being achieved, even though the above instabilities made fine tuning difficult. The spectra indicated the presence of the ^3D levels but no trace of the ^3P states, showing that the decay from ^3P to ^3D was less than 5 microseconds.

To improve the stability of the dye, a circulating system was installed to reduce any thermal or depletion effects. No improvement was noticed, however. It was discovered that the dye was very sensitive to room light and perhaps also to the flash-lamp light of the ruby laser. A cover for the dye laser was built with filters for the input and output pulses and this increased the length of time that the dye could be used but did not solve the shot to shot instability.

A separate detector for the dye output was built so that any correlations between the dye output and possible smaller instabilities of the ruby pump could be seen. Such a correlation was found. Since the ruby instability was due to poor cooling, the heat exchanger was replaced with an independent cooling system. The output of the ruby was now stable to better than 5% which led to the acceptable stability of the dye output of 10%.

To solve the problem of damage to the grating the aluminum coated replica was coated with gold which absorbs only 2.3% at 791.1 nm compared with 13.7% for aluminum. In addition another dye (HITI in DMSO) was tried in the hope that it would have higher gain and allow the dye lasing area to be increased, thus decreasing the possibility of damage. This dye lased at $8.0 \text{ nm} \pm 5 \text{ nm}$ with a broad band back mirror in the cavity. However it was felt that the output could be pulled to 791.1 nm with the grating. Installation of the gold coated grating indicated that the damage problem was still not solved, since burn marks quickly developed at energies 0.1J. The tentative plan is to replace the grating with a Fabry-Perot.

Dr. Mitchell has continued work on the magnesium pumping experiment which employs a flashlamp-pumped dye laser to excite the intercombination transition in Mg I at 457.11 nm.

Following mechanical failure of the coaxial flashlamp and dye-cell assembly employed in the laser, and inefficient pumping arising from filamentary discharges in the replacements assembled here, a commercially available lamp having a permanently sealed xenon-filled discharge region was purchased and has so far proved satisfactory.

The output of the untuned dye laser was examined with a 1.5m grating spectrograph. A broad band in the region 452-463 nm was observed. Coarse spectral tuning of the laser output was achieved by replacing the total reflector of the cavity with a blazed reflection grating operating in autocollimation in the first order. A continuously tunable output in the region 455-464 nm was obtained, the spectral width of the emission being 0.4 nm.

Further improvements in laser performance were made by acquiring a dye sample of higher purity, increasing the volume of solution in the system, modifying the flow system to achieve adequate aeration without bubble formation, optimizing the flow rate, and replacing the output reflector with one of better optical quality and reflectivity around 50%. Measurement of the output energy with a calibrated photodetector indicated that about 30 mJ was available in the 0.4 nm width of this coarse-tuned output.

Further spectral narrowing was achieved by inserting a non-coaxial Fabry-Perot etalon into the laser cavity. The reflectivity of the dielectric coatings is 74%, and the outer surfaces are antireflection coated to minimize the reflection loss. The adjustable gas was initially set to 0.8 nm, yielding a free spectral range of 0.13 nm at 457 nm. Because of the increase in threshold it became necessary to replace the output mirror with a total reflector and take the output from the zero-order reflection from the grating. The resulting laser spectra consisted of from 2 to 6 narrow lines, separated by the 0.13 nm free spectral range of the etalon. The true spectral width of the components has yet to be determined, but it is definitely not more than one-tenth of the free spectral range and is possible much less. The maximum energy achieved so far with this configuration is 3 mJ, but a number of factors remain to be optimized, in particular the dye cell alignment, which has been found to be rather critical.

With the gratings presently available, the 1.5 m spectrograph did not permit operation in the first order below 380 nm, and difficulty was encountered below 250 nm with overlapping orders.

To circumvent this difficulty, the laser, Garton flashlamp and vapor oven, together with associated equipment, were moved, so that the Jarrell-Ash 3.4m Ebert spectrograph could be used. In addition to allowing operation in the first order, this instrument offers larger dispersion and greater versatility in operation.

Dr. Mitchell has also set up the heat-pipe furnace and the associated quartz optics. This has been tested with argon buffer-gas pressures between 10 and 20 torr, and as expected, the strong ground-state absorption line in Mg I at 285.21 nm was very readily observed. So far there is no apparent coating or corrosion of the furnace windows, suggesting that the heat-pipe mechanism is operating as intended.

THEORETICAL WORK

Theoretical calculations of cross-sections necessary for determining the populations of high atomic levels under coronal conditions have been made by J. Black, a Harvard College senior, as part of an independent study program under the direction of A.K. Dupree. He has obtained rate coefficients for collisions between protons and electrons and highly charged positive ions. These can be incorporated into an existing code to predict the populations of high levels involved in the radiofrequency transitions.

The search for radiofrequency recombination lines from the solar atmosphere was continued at the Haystack Facility of MIT with three days of observations (17-19 March 1971) at a frequency of 236 Hz. The observing program was carried out in

collaboration with M. Simon and P. Berger of the State University of New York at Stony Brook. Unfortunately instrumental problems of known and unknown origin plagued the attempt to detect weak radio lines against the strong solar thermal continuum. Further observations at the more optimum frequency of 936 Hz by Simon and Berger at Kitt Peak yielded an upper limit to the line temperatures in the quiet sun; observations of active regions are scheduled for this fall. We plan no further observing program for Haystack until the completion of observations at 936 Hz.

The process of dielectronic recombination which is believed to be operative in the corona may be confirmed by observation of radiofrequency recombination lines in the corona, or perhaps in other low density, high temperature sources such as supernova remnants. These possibilities were discussed by Dupree as an invited participant in the "Symposium on the Gum Nebula and Related Problems," at Goddard Space Flight Center in May, 1970 (1971, in press, ed. S.P. Maran, J.C. Brandt and T.P. Stecher, NASA).

Dupree has also been investigating the effects of collisions and incident radiation fields both thermal and non-thermal upon the population of atomic levels. This has application in the solar atmosphere where diagnostic techniques (such as that found for ions of the Be sequence) are extremely valuable. Additionally, the interstellar medium produces recombination lines which require quantitative evaluation of the populations of high levels. Techniques have been developed to determine the electron temperatures and densities of cold hydroxyl clouds by using intensity ratios of α and β transitions observed in the direction of H II regions.

Dr. Withbroe has continued his work in solar physics, among his recent publications on the subject is a review paper for the Menzel Symposium entitled "The Chemical Composition of the Photosphere and Corona," which will be published in the proceedings of the symposium (Harvard College Observatory Symposium on Astrophysics in Honor of Donald H. Menzel, April, 1971).

In preparation for the experimental line broadening work with the piston compressor, Mr. M. Eckart has been reviewing fundamental theories on the subject. The so-called relaxation theory utilizing the Liouville equations of motion and the Zwanzig projection equations, was studied in depth, as were Green functions in many-body problems with their associated diagrams. At the present time, the validity of the so-called unified theory of Smith, Cooper and Vidal is under consideration.

SPECTROSCOPY

Dr. G. Tondello has completely assembled the flash pyrolysis equipment. A condensor bank of 120 μ F KV was used for the excitation of the flashlamp; a second condensor of 14 μ F 20 KV used with a spark-gap provided the energy for the Garton source. A new grating of 1200 lines/mm blazed at 125 nm was mounted on the 3m McPherson spectrograph, aligned and focused.

The performance of the grating was such to allow absorption spectra to be recorded on the Kodak 101-01 film with an entrance slit of 30 μ in a single shot.

The materials of which absorption spectra have been recorded with the pyrolysis technique are:

Cu I. This spectrum shows interesting autoionized resonances in the region 100.0 - 170.0 nm and the analysis of it supplements the previous work by Shenstone. Some 60 lines normal and autoionized have been classified and the shape of the continuum absorption has been measured together with the parameters of the autoionized features.

Fe I. Following a theoretical analysis by H. Kelly, described here during the Menzel Symposium in April 1971, we began an experiment to study the shape of the continuous absorption of Fe I. A very interesting spectrum has been produced showing strong resonances in the continua in the region 80.0 - 160.0 nm. This spectrum is now under study and the experimental material will be supplemented by a furnace experiment.

In addition the flash pyrolysis technique has been applied to the production of ionized species; especially, low ionization potential elements. For material with I.P of the order of 5-6 eV practically all the material is in the first ionization stage with no visible contribution from the neutral. The work has started with the production and photography of La II, Ba II and Y II spectra.

The work on Fe I oscillator strengths determined from anomalous dispersion of shock-heated gases has been completed (Huber and Parkinson 1971, Parkinson 1971). We measured gf-values for 81 lines in the wavelength range 360.0 - 453.0 nm. Within the given errors these values agree with oscillator strengths obtained by other methods, including wall-stabilized arc and shock tube emission, the beam-foil technique, and delayed coincidence measurements; except that the data reported by us tend to be somewhat

higher. The recent NBS measurements by Bridges and Wiese (1970) show the best agreement with our results.

Drs. Banfield and Huber took a series of hook spectra of furnace-heated Fe vapor that cover the wavelength region 200.0 to 400. nm. All plates contain at least one spectrum showing hooks around the 372.0 nm resonance line; the column density $N\lambda$ of Fe thus can be determined because the f-value of this line is now well known. These plates are currently being measured by Mrs. Omotoso. Preliminary results indicate discrepancies with the only available f-values in this wavelength region (Corliss and Tech 1968) that increase toward shorter wavelengths and may reach a factor of ten at 2000 Å; the literature data seem to be too high.

Preliminary investigations aimed at measuring the absolute cross-section of the photoionization continuum of Fe were also performed on the Mach-Zehnder instrument. So far we established that it will be feasible to perform such an experiment, in spite of the fact that CO absorption bands in the region of the photoionization edge can probably not be avoided.

Dr. Kohl has measured a preliminary value for the Al I photoionization cross-section at the first ionization limit of 23 mB to an estimated accuracy of 30%. The most troublesome parameter to ascertain in the measurement is the Al I density in the shock heated plasma and consequently this quantity was determined by using both a chemical equilibrium calculation and an equivalent width measurement of the 219.92 nm line of Al I for which the f-value has been measured elsewhere. The latter determination is hampered by the difficulty in selecting the appropriate curve of growth and the accuracy of the published

f-values for weakly absorbing lines.

It is generally recognized that the anomalous dispersion or hook-method provides a precise measurement of the f-value density produce and a hook-measurement would take full advantage of several recent Al I lifetime measurements which are in excellent agreement for the strong lines. Because of the increased accuracy of the hook method, the final data for the Al I photoionization cross-section and autoionized lines will include a hook-measurement of the 396.15 and 394.40 nm lines along with an early simultaneous absorption measurement of the continuum. To this end, a Mach-Zehnder interferometer has been remounted for use in a vertical orientation, the optics have been recoated, and the instrument has been adjusted for white light fringes.

Drs. Parkinson and Reeves have completed the experimental work on the autoionization resonances and configuration mixing in the emission spectrum of Cd I. The absolute photometric measurements of the lines resulting from the transitions $5p^1P_1 \rightarrow p^2(x^3P_2 + y^1D_2)$ and $5p^3P_1 - p^2(x^3P_2 + y^1D_2)$ and the photoionization (sd^1D_2) continuum have yielded the values of the mixing coefficients (x and y), the lifetimes of the autoionizing state and the capture cross-sections for the lines and nearby continuum. Work is now underway on similar features in the Zn I spectrum which upon completion will be included in a paper describing both spectra.

Work was continued by Dr. T. McIlrath and Mr. J. Carlsten on the theory of the interaction of intense coherent radiation with atoms. The previous theory was extended to include the more applicable case of multi-mode pulsed lasers. It was found that for the experimental situation we have, the solution reduces to

that of an intense, incoherent light source.

These calculations indicate that, for the barium experiment, energies being obtained with the dye laser are easily high enough to equalize the population of the ground and excited states for any given atom. The problem thus reduces to one of having enough photons in the absorption line width to excite all the atoms in line of sight. Since one would like to be able to see cross-sections on the order of several megabarns we will need about 10^{17} excited states, which corresponds to $\chi \sim 30$ mJ within the line width of the absorption line. To achieve this goal additional dispersive elements such as another Fabry-Perot will have to be placed in the dye laser cavity to obtain a line width commensurate with that of the absorption line.

The theoretical calculations were compared to the preliminary results of the calcium experiment and found satisfactory. This work is now being prepared for publication.

The process of microdensitometering the plates containing optically pumped calcium spectra was finally completed and the data were transferred to tapes. Programs were developed to attempt to establish excited state number densities by measuring ground state depopulation after a laser pulse. The results provide a useful and important constraint on the populations but were less useful than had been hoped. The difficulty originated in the fact that most of the plates were taken at too high a calcium vapor pressure for the depopulation to be measured accurately. The high vapor pressure was required to observe the autoionizing lines out of the ground and excited states. These

lines were the only ones that could be resolved and were therefore the only ones unambiguously on the linear portion of the curve of growth. At lower vapor pressures an obvious and gross depopulation of the ground state could be observed by looking at the principal series and it is clear that the problem is not that the laser fails to alter significantly the atomic populations.

The first stages were completed in converting the spectra to equivalent widths for the absorption lines out of the calcium excited states. Curves of growth were plotted using relative oscillator strengths derived by other workers from furnace absorption spectra and were put onto an absolute scale by using a published lifetime measurement. It was found that at high buffer gas pressures the experimental points extended onto the linear portion of the curve of growth. This plot can now be used to obtain the oscillator strength for the autoionizing lines which originated from the excited states. By using these data we now can determine the excited state number densities for all of our plates. The reduction of the calcium data is now well under way and will be continued enthusiastically into the next semiannual report.

Mr. J.W. Allen has continued his analysis of OH and CH bands obtained with a shock tube. As has been discussed in the previous progress report, a spectral synthesis approach has been adopted here to determine integrated absorption coefficients from intensity data. Overlapping line profiles of low signal to noise ratio with significant distortion due to instrumental effects required the use of this approach. Since all measurements of half widths and central depths are made on intensity computer plots, these widths and depth values had to be converted to the corresponding optical depth values before the profiles could be

calculated. The accuracy of this conversion has been greatly improved compared to the technique employed six months ago. Furthermore, various methods have been incorporated to speed up the calculations.

To study the effects of the wing structure of the instrumental profile, spectra of a mercury-198 lamp were recorded and reduced to intensity. Ten Rowland ghosts were apparant with $\pm 2\text{\AA}$ of line center. Calculations with the synthesis program indicated errors of up to 15% in the integrated absorption coefficient caused by neglect of this wing structure. Since the instrumental profile varies significantly across a spectrogram, it was necessary to scale each ghost according to the central peak (determined from thorium spectra) and then generate complete instrumental functions for twelve regions of the spectrogram.

All OH and CH spectra considered useful for analysis have been densitometered. Also, the reduction to intensities and measurement of central intensities, half sidths, and central positions have been completed for OH. Most of the OH data have been prepared for the synthesis program.

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