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Improved Experimental and Theoretical Energy Levels of Carbon I from Solar Infrared Spectra

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Abstract

We have improved the energy levels in neutral carbon using high resolution infrared solar spectra. The main source is the *ATMOS* spectrum measured by the Fourier transform spectroscopy technique from 600 to 4800 cm-l, supplemented by the *MARK IV* balloon data, covering from 4700 to 5700 cm-l. From these infrared data, we have determined 19 new energy levels in the 5f, 5g, 6g, and 6h configurations. For completeness' sake, we include the 63 new levels found by Feldman *et* al. plus 10 new levels derived from the VUV data. Utilizing all existing carbon spectra from the far infrared to the vacuum ultraviolet, we have revised Johansson's energy levels and the ionization potential, resulting in improving the accuracy by about an order of magnitude to about 3 mK. Finally, we report on our attempt to improve the accuracy of the reclusive 4d $^1F_3$ level and the problems of blends and associated line identifications.

I. INTRODUCTION

The term system of neutral carbon has been evaluated by Johansson [1] in his classic work [hereafter Job]. Generally, the lowest and the highest levels were determined from vacuum ultraviolet (VUV) spectra, primarily those of Junkes *et* al. [2] with accuracies varying from 0.1 to 0.9 cm-l (0.002 to 0.01 Å). For the levels in between, Johansson has made extensive measurements in the extended visible (Job) and in the near infrared with Litzen [3], referred as JL. Both sets of measurements have much improved accuracies of about 0.02 cm-l . Using the essentially unperturbed np $^3D_3$ series up to n= 10, he was able to determine the ionization limit with an estimated accuracy of 0.1 cm-l . While most measured levels were accurate to 0.02 cm^{-1}, Johansson pointed out that the 4d $^1F_3$ level could only be determined from two VUV lines, so its error might be as large as 0.5 cm-l . Other levels given to one decimal (with *) have been extrapolated and their errors may be a few cm-l .

His work has been adopted in its entirety by Moore [4], who noted that small but insignificant improvements in the lowest few levels could be made with the more precise VUV data of Herzberg (H) [5] and of Kaufman and Ward (K W) [6]. These VUV lines can now be combined with the high precision far-infrared measurement of the ground state sub-levels by Saykally and Evensson [7] to improve the upper levels. The levels, in turn, become the foundation of improving the entire term system utilizing solar infrared Fourier transform spectra in this work.

Recently, one of us (Geller) has analyzed the space-based mid-infrared (MIR) solar spectra *ATMOS* from 2 to 16 microns (600 to 4800 cm-l) with precision of 1 mK (0.001 cm-l) for strong unblended lines. His line list [8] includes over a hundred lines belong to (neutral) carbon. Also available are the balloon-born ***Mark IV*** solar spectra [9], extending the wavenumber to 57oO cm-l , with comparable precision. In this work, we report on the identification of some 20 new energy levels based on these spectra. Simultaneously, we have improved the precision of the known levels to a few mK in most cases, up to the 4p ^3P sub-levels.

Of particular interest is the $4d\,^1F_3$ level, whose position is known to perhaps 0.5 cm-l through 2 VUV lines [1,2], as it has not been observed in any other spectra. We expect to observe it in infrared lines of the *ATMOS* spectra, especially in the 4d-5f array at 4 microns. To facilitate line identification, we first study the analogous 3d-4f array, whose oscillator strengths have been accurately calculated by Hibbert *et al.* [10]. These gf values support the rules Johansson used to assign a particular sub-level of the pair-coupled 4f in a transition. We are also able to locate the missing 5f′ [4 $\frac{1}{2}$] pair, which could not be accessed from the 2p’ level, unlike all the other 5f levels found by Job.

Previously, Geller has identified certain high ℓ Rydberg levels [8], using theory based on somewhat uncertain values for the core parameters [11]. Recently these values have been precisely measured by Ward and Lundeen [12], thereby improving the calculated levels. Together with oscillator strength considerations, they cast doubt on the previous identifications and suggest that those lines should be replaced by neighboring weaker lines. The present assignments include the entire 5g and 6h complexes, as well as all but one of the 6g levels.

As mentioned before, the VUV data have provided crucial connections of the levels determined from the IR spectra to the ground state, For the sake of completeness, we revisit the laboratory VUV data as compiled by Kelly [13], augmented by the solar spectra of Feldman *et al.* [14] and of Sandlin *et al.* [15]. By averaging *over* the 3 sets of data, we are able to improve the new nd (and ns) levels found by Feldman *et al.* in their VUV solar flare spectra, and in some instances to derive new levels. In the present work, our goals are to find new levels of the neutral carbon aton and to improve the accuracy of known levels using all available sets of spectra. Levels given here are usually accurate to a few mK, representing an improvement over Joh by one order of magnitude.

II. INFRARED SPECTRA

The infrared spectrum of carbon had been studied in the laboratory by JL from 3900 to 8600 cm-l (1. 1 to 2.6 μn). The wavenumbers of the 75 emission lines were determined by a Fabry-Perot interferometer, with accuracy estimated to be 20 mK; most of the lines were confirmed by ground based solar data. We now extend their work farther into the mid-infrared (MIR),utlizing space-based and balloon-borne solar spectra to be described below.

A. Infrared C I spectrum in the *ATMOS* data

The *A TMOS* spectra, covering the range of 600 to 4800 cm-l (2 to 16 μn), were taken of the solar disk center from a low-orbit satellite. These spectra, described in our recent works on Fe I [16], were taken with high resolution FTS, and were capable of an accuracy of 1 mK for unblended lines. In addition to improving the accuracy of the energy levels, we seek to to confirm Johansson's identification of the 4d $^1F_3$ level through only two VUV lines. As in our works on Fe I, we will explore the high ℓ Rydberg lines, e.g. 4f-5g at 4 μn, 5g-6h at 7 μn, etc. Table I shows the neutral carbon line list from the *A TMOS* spectra. The list differs somewhat from that previously published by Geller [8] as follows: new lines have been identified and added, some identifications have been rejected and put into Table III, and lines marked by an asterisk have been determined by fitting the profile to a Lorentzian function. This procedure is found to give line centers with greater self-consistency.

In Table I, the calculated wavenumbers are usually taken from Bièmont and Grevesse [17] (same as Job). For the high ℓ levels not on that list, we use the theoretical levels kindly supplied by Lundeen, calculated with his core parameters [12]. From 3800 to 4800 cm-l , our spectra overlap with that of JL, so for the purpose of verifying our line identification their measured wavenumbers are used in column 2 rather than calculated ones. It is evident that our sensitivity is substantially higher than theirs, as we observe many weaker lines absent in their list. Note that the wavenumbers of the two sets of lines agree to 0.02 cm-l , which is the stated accuracy of the JL measurements.

B. The *MARK IV* spectra

The *MARK IV* solar spectra extend our wavenumber coverage to 5700 cm-l , with accuracy comparable to the *A TMOS* spectra. However, as the line centers in Table H are not found by fitting to a profile, the accuracy in wavenumbers suffers as the noise level increases with frequency. In the regime where Mark *IV* overlaps with ***ATMOS*, *(4700-4800*** cm-l), the **measured wavenumbers** in the two sets agree to 3 **mK** for unblended lines; further, their intensity scales are adjusted to be the same. However, 3 pairs of blended lines at 4702,4717, and 4725 cm-l , shown in Table II, have a typical separation less than the fitted FWHM of about 0.2 cm-l . In **these** cases, the two components are only partially resolved, and the wavenumbers in the two sets may differ by 0,01 cm-l . We believe that ***energy levels*** derived from these spectra are typically accurate to 3 **mK** up to about 5400 cm-l , which is almost an order of magnitude better than the existing data by **Johansson** and collaborators. However, from 54OO to 5700 cm-l , the accuracy is no better than 0.01 cm-l .

111. IMPROVED TERM SYSTEM

We begin with the energy levels of **Johansson** [1], whose classic work combined his measurements in the **photograhpic** (extended visible) and in the near infrared [3] regimes with the earlier VUV works. Results of recent VUV measurements have been compiled by Kelly [13]. Using **Johansson's** energy levels, we generate a line list in the infrared, obeying **Laporte's** rule and the angular momentum selection rule, A J $\leq$**1.** These calculated **wavenumbers,** displayed in column 2 of Tables I-III, are required to come within 0.1 cm^{-1} of an observed line to constitute a possible identification. The observed line intensities (depths) are then compared with the accurate gf **values** of **Hibbert** ***et al*** [10], which incorporates multi-configurations and relativistic effects. Good agreement is found for most lines (within a factor of two) by assuming a solar temperature of 51OOK at 1000 cm-l to 6800K at 5000 cm-l , according to the Harvard-Smithsonian VAL model [18]. For higher excitation lines, gf values are adopted from less accurate sources [17,19], including hydrogenic values for high ℓ Rydberg transitions. Lines passing both the wavenumber and intensity criteria are listed in Table I for the ***A TMOS*** data and in Table II for the ***MARK IV.*** Those lines that we deem to be false coincidences, usually with gf values which are too small and so failing the intensity test, are relegated to Table III. Specifically, we find that the line intensities are generally proportional to the gf values, provided that the lines have nearly the same excitation energy and lie in the same spectral region. Otherwise, the conversion factor **(CF),** which converts the gf value to the observed intensity, increases with the excitation energy and as the line frequency **decreases** (owing to the increase in the height of line formation and hence the decrease in solar temperature).

A. The triplet system

The most accurate fine structure splittings are those of the triplet ground configuration, which have been measured by high precision far infrared (FIR) spectroscopy [7] to an accuracy of better than 0.1 **mK** (1 **mK=0.001** cm-l). These can be utilized to improve on the precision of the upper levels of the four-decimal-place VUV lines [13], which have a precision between 0.0006 and 0.001 **Å.** Thus, the 3s ***3P"*** sub-levels are found with a precision of 0.020 to 0.036 cm-l , when appropriate averages are taken; they are consistent with the values given by Job.

Similarly, the $2p^3\,{}^3P$ and ^3D sub-levels can also be determined with comparable accuracies. However for the **λ1329** lines in the latter case, there exist three sets of measured values. The first was measured by **Herzberg** [5] and cited by Moore [4]. Subsequently, his **dat** a were slightly modified by **Edlèn** [20], and adopted by **Herzberg** as the **I.A.U.** standards [21]. These two sets differed up to 0.0004 **Å, which** was **still** well within the uncertainty quoted by **Herzberg** of 0.0007 **Å.** Following Kelly [13], we adopt **Edlèn's** modifications, and discard the first set **(Herzberg's** original data). The third set was the independent measurements, of Junkes ***et al.*** [2], with a larger quoted error of 0.002 **Å.** Of the 6 lines in this **multiplet,** one line, the only VUV line leading to the $2p^3\,{}^3P_0$ level, had a significant discrepancy of 0.0011 **Å,** which amounted to 0.06 cm-* . Evidently, Johansson chose the Junkes ***et*** al. line, as it led to a value of -2.156 cm–l for the $^3P_1$-$^3P_0$ interval, which agreed with -2.13 cm–l from the **IR** data of JL; the corresponding value from the second set was -2.088 cm-l . Eliminating the controversial $2p^3\,{}^3P_0$ level from consideration, we calculate from both sets of VUV data the term values of 75253.985(9) and 75255.285(7) cm-l for the $2p^3\,{}^3P_1$ and $2p^3\,{}^3P_2$ respectively. The number in parenthesis are the statistical errors from averaging 6 and 4 levels. For convenience, we collect all our improved levels in Table IV, where the revised energy levels are given in the same format **as** in the work of Moore [4], except that we delete the first column **(config.)** for brevity. In addition, we display the interval only when it is measured to **a** higher accuracy than the given levels and replace it with the number of lines used to determine that particular level as a measure of its accuracy.

Actually, the fine structure intervals can be evaluated with even greater precision from the ***A TMOS*** data, For example, the MIR lines in Table 1 give the fine structure intervals of the $2p^3\,{}^3P$ spectroscopic term with great consistency from transition arrays to each of the following 4 terms: 3p ^3D, 3p ^3S, 3p ^3P and 4p ^3D. Our value of -2.172 cm-l is quite close to **Johansson's** adopted value of -2.15 cm-l , but not to -2.088 cm-l from the **Edlèn** values. If we adopt **Johansson's** $2p^3\,{}^3P_2$ level, we can determine the remaining levels from these 4 transition arrays. In particular, our term values for the $2p^3\,{}^3P_1$ and $2p^3\,{}^3P_2$ from the MIR data are 75253.975 and 75255.270 cm-l . Comparison with the term values from the VUV data suggests that **Johansson's** triplet levels should be increased by 0.012 cm-l , which is in accord with the suggestion of KW **as** echoed by Moore.

As in Job, the VUV lines are also used to find the $2p^3\,{}^3D$ sub-levels: In fact our $2p^3\,{}^3D_1$ level is determined in principle by 3 VUV lines from the **λ1560 multiplet** of KW. However, two of the **lines** are severely blended, so we weight the position heavily towards the unblended line, resulting in a term value coincident with **Johansson's.** The other two sub-levels can be determined from lines in the ***Mark IV*** spectra in Table II.

While the first 3 arrays yield intervals and levels **in** agreement with Joh usually within 0.01 cm-l , the last array produces one notable exception. Johansson has determined the 4p $^3D_1$-$^3D_2$ interval to be 18.76 cm-l from weak transitions to the 3s ^3P and to the 2p' ^3D terms. However, there is considerable internal inconsistency, **as** some of his lines deviate as much **as** 0.05 cm-l from his calculated values. In our spectra, the difference in wavenumbers between pairs of lines connecting these levels to 4s $^3P_1$, 4d $^3F_2$, 5s $^3P_1$, and 3d $^3D_1$ gives 18.826, 18.830, 18.835, and 18.844 respectively. The average value is in excess of 0.06 cm^{-1} larger than Job, but is not incompatible with his spectra. So we are compelled to revise his 4p $^3D_1$ downwards by almost 0.08 cm-l , while leaving the other members of the triplet essentially unchanged. Other intervals and levels are found in a similar fashion; our triplet levels seldom differ from **Johansson's** by more than 0.02 cm-l .

B. The singlet system

The singlet is connected to the triplet system through 2 inter-combination **lines,** labeled i, in Table I, with excellent coincidence in **wavenumbers.** Line identification is supported by comparison of the line intensity ratio to the theoretical gf value ratio. For instance, the ratio of the **intercom**bination 3p $^1S_0$-3d $^3D_1$ line to the singlet 3p $^1S_0$-3d $^1P_1$ agrees with the gf value ratio, both being about 0.2. The above triplet level is re-connected back to the singlet system by the other **inter**combination line 3d $^3D_1$-4p $^1D_2$. Again, its observed intensity ratio to the triplet 3d $^3D_1$- 4p $^3P_0$ line agrees with the theoretical gf value ratio of 0.6. Note that the above two intercombination lines link 2 singlet levels, 3p $^1S_0$ and 4p $^1D_2$, which are connected through the 3d $^1P_1$ level by two allowed transitions found in Table I. By summing the wavenumbers using first the allowed and then the forbidden transitions, the Ritz combination principle is found to be satisfied to 3 mK. From the stronger intercombination line at 4317.590 cm-l , we place the 3p $^1S_0$ level at 73975.919 cm-l , which is only 9 **mK** above **Johansson's** value.

The rest of the singlet system is rather easy to analyze, utilizing singlet lines from Tables I and II. We find most singlet levels with excellent self-consistency to within a few mK, and in agreement with **Johansson's** values **within** his stated overall accuracy of 0.02 cm-l . Several exceptions are noted below. Johansson found the 4p $^1D_2$ level through only one line (in emission to the 3s $^1P_1$ level) which has an uncertainty of 0.08 cm-l . We have determined that this level is actually 0.07 cm^{-1} higher, as all 3 lines originating from 4s $^1P_1$, 3d $^1P_1$ and 3d $^1D_2$ lead to the same level. On the other hand, Johansson's 4d $^1D_2$ level appears to be well determined from 2 lines originating from 3p $^1P_1$ and from 3p $^1D_2$ with uncertainties of about 0.03 cm-l . We find that it **has** to be lowered by 0.05 cm-l , based primarily on the transition from the 4p $^1P_1$ level (which has been revised upwards by 0.023 cm-l). This revision also agrees with the blended line originating from the aformentioned 4p $^1D_2$ level to about 0.01 cm-l .

Finally, Johansson found the 5s $^1P_1$ level through 3 lines originating from 3p $^1P_1$, 3p $^1D_2$ and the intercombinational 3p $^3D_2$. However, the internal inconsistency was **as** large as 0.10 cm-l . We find that this level has to be raised by 0.11 cm^{-1} , largely due to the line originating from the

4p $^1D_2$ level (which we have revised upwards by 0.07 cm-l). This revision is further supported by the weak line from the 4p $^1P_1$ (with a discrepancy of 0.02 cm-l and by the blended line from the 4p $^1S_0$ (with a deviation of -0.04 cm-l). The unusual case of the 4d $^1F_3$ level will be addressed in Sec. IIID. The next level, the 4d $^1P_1$ level, is essentially in agreement with Johansson. However, singlet levels beyond this level are generally connected by weak and blended lines, and so we cannot improve upon Johansson's energy levels.

Singlet levels below 3p ^{1} So are not covered by transitions in the *A TMOS* data, so they may be improved only with less accurate data. KW have measured 7 singlet VUV lines to 4 decimal places with accuracies of 0.001 Å(0.05 cm-l). Using our values for 3d $^1D_2$ and 3d $^1P_1$, their VUV lines give the 2p^2 $^1D_2$ level with a discrepancy of only 8 mK. Taking the average, we find that our value for this level in Table IV is 46 mK above Johansson's, and is in rather good agreement with KW'S revision of 30 mK, using only their VUV lines. We have left out the value determined from 3d $^1F_3$, which is discrepant by 41 mK, as this level is found only through one blended MIR line. Similarly, the 2p^{2}1 So level is determined through our values for 3d ^{1}PI,'4d $^1P_1$, and 5d $^1P_1$ levels. Taking the average weighted by the VUV line intensities, we find that our value for this level is 24 mK higher than Johansson's, and is compatible with KW's upward revision of 10 mK. From our value for 2p^2 $^1D_2$ and their VUV line, we find the 3s $^1P_1$ level to be 26 mK above his value. With this level, we revise the 3p $^1P_1$ level with the near IR line from JL to 36 mK above Johansson's. Similarly, the 3p $^1D_2$ level is revised with the *MARK IV* line [9] to be virtually coincident with his value.

C. The nf levels

Following Moore [4], we use the jK pair-coupling scheme to describe the nf (including the nf') levels. As in the work of JL, our 4f levels are found through the 3d-4f transition array. However, the improvement in detector technology is evident, as Tables I and 11 show weaker members of the array, which were not detected in their work, On the other hand, our solar spectra are limited to frequencies below 5700 cm-l , and miss 8 of the 20 lines in the 3d-4f transition array measured in the JL laboratory spectrum. The 4f levels derived by JL from the 3d-4f array are expected to be accurate to 0.02 cm-l and they are further supported by the **2p′-4f** array near 4000 **Å,** which are accurate to 0.08 cm^{-1}. Except for blends, our revised 4f levels are accurate to 3 mK; they are found to be generally within 0.02 cm-l of **Johansson's values.**

The 3d-4f (and the **4d-5f)** lines provided further links between the singlet and the triplet systems as well **as** to the high ℓ Rydberg levels through the critical 4f-5g transitions. In the work of **JL,** lines were assigned to a particular member of the pair of 4f sublevels according to a set of rules. These rules are ***now*** verified by actual gf values for the entire 3d-4f transition array as calculated by **Hibbert *et al.*** [10] shown in Table V. Also shown are the observed line intensities and the **wavenumbers** (integer only, to facilitate line search). For the first 4 spectroscopic terms, the **wavenumbers** are outside of our infrared data range, so the observed intensities are taken from JL. Note that lines **with** gf values less than unity are not observed and those observed have intensities about 1.2 **times** their gf values (**CF=** 1,2). Lines from the next 5 spectroscopic terms fall into the range of the ***MARK IV*** data whose line intensities are displayed. Here'lines with gf values below 0.2 are not seen and the observed lines have intensities with the **CF=5** approximately. Turning to the last 3 spectroscopic terms whose line wavenumbers fall into the ***A TMOS*** regime, we note that the conversion factor is also about 5 **as** expected. While most of the lines in Table V have the expected intensities, two lines at 5390 and 5483 cm-l appear to be too strong by half and by one order of magnitude respectively. It is not known whether the intensity discrepancies are due to inaccuracies in the calculation of smaller gf values or to blends with unknown lines.

The 5f levels of JL came from the **2p′-5f** array with accuracies ranging from 25 to 50 mK. In contraEt, our 5f levels are derived from the 4d-5f array, analogous to our 4f levels from the 3d-4f array. Taking advantage of the similarity, we calculate their gf values in the 4d-5f array by scaling them to the 3d-4f gf values in Table V. **The** scaling factor is almost unity, according to the **4d-5f:3d-4f** ratios calculated by Victor and **Escalante** (VE) [19]. (In the LK coupling scheme, all 3 oscillator strength ratios for nd $^1F_3$-**mf** D, nd $^1F_3$-**mf** F, and nd $^1F_3$-**mf** G turned out to be nearly equal, about 0.84.) The observed line **intensities** in the 4d-5f array generally obey the pattern in Table V and can be estimated by using **CF=0.15.** As expected, these higher excitation 4 micron lines are much weaker than those 2 micron **lines** in the 3d-4f array. Further, the 5f pair is often blended, so the accuracy of our 5f levels is lower than others, perhaps around 10 mK. Nevertheless, our accuracy is still considerably better than that of JL; the discrepancy between their and our 5f levels varies from a few **mK** to almost 100 mK.

Since JL could not mea.sure the **5f'** $[4\frac{1}{2}]$ level (inaccessible from the 2p' configuration), we have to estimate the position of this level from theory. By scaling the pair-averaged energy difference $[4\frac{1}{2}]$-$[1\frac{1}{2}]$ of the **5f'** to the known **4f'** by n^{-3} [11], we predict the j-K coupled **5f'** $[4\frac{1}{2}]$ level to be at 86488.20 cm-l . So theory places the 4d $^3F_4$-**5f'** $[4\frac{1}{2}]_5$ line at 2689.63 cm--l , with intensity of 1.2, which matches well the ***ATMOS*** line at 2689.415 cm-l with exactly the expected intensity. Similarly, we identify 4d $^3F_3$-**5f'** $[4\frac{1}{2}]_4$ line at 2726.720 cm-l with the appropriate intensity of 0.3. Using our revised 4d $^3F_3$ and 4d $^3F_4$ levels, we determine the new **5f'** $[4\frac{1}{2}]_4$ and **5f'** $[4\frac{1}{2}]_5$ levels in Table IV. From the new levels, the calculated 4d $^3D_3$-**5f'** $[4\frac{1}{2}]_4$ line almost coincides with an observed line at 2639.178 cm-* . However, the gf value predicts an intensity too low to be observable by an order of magnitude, so this line is relegated to **coincidental** lines in Table III. We search for the missing **6f'** $[4\frac{1}{2}]$ level, calculated at 87832.33 cm-l in a similar manner. However the predicted intensity for the 4d $^3F_4$-6f' $[4\frac{1}{2}]_5$ line is only 0.2. The calculated position 4033.15 is close to a strong CO line at 4033.211 cm-l and in fact near a CO overtone bandhead, so the weak line would be undetectable. As other lines in the 4d-6f array have predicted intensities at or below the detection limit of 0.1, we abandon the search for 6f (and higher nf) levels.

D. The enigmatic **2p4d** $^1F_3$ spectroscopic term

In his seminal work on the spectrum of C I, Joh determined the energy levels of the nd $^1F_3$ series, from emission lines to the 3p $^1D_2$ spectroscopic term. These levels were verified by the less accurate VUV lines from transitions to the $2p^2$ * D_2 and the $2p^2$ $^3P_2$ terms. However in the enigmatic case of n=4, the near **IR** line **was** too faint to be observed by **Johansson.** So the 4d $^1F_3$ level was found through his analysis of the VUV spectra of **Junkes** ***et al*** [2]. Specifically, he proposed that the line **λ1355.844 was** the $2p^2$ $^1D_2$-**2p4d** $^1F_3$ transition, which **was** also observed at 1355.825 Å by **Paschen** and Kruger [22], **His** proposal was supported by the **intercombination** line **λ1191.838** through the Ritz combination principle. The uncertainty of those lines was **±0.01Å,** which corresponded to ± 0.5 **and** 0,7 cm–l respectively.

More recently, these 2 lines have also been observed in the VUV solar spectra. Feldman ***et al.*** [14] identified these lines at 1191,837 and 1355.843 **Å** with an uncertainty of 0.004 **Å.** They were also able to extend this series from n=8 to n=29, using MQDT analysis to be discussed in Sec. IVB. Compiling the entire line list of the solar atlas from 1175 to 1710 **Å, Sandlin** ***et*** al. [15] showed these 2 lines at 1191,834 and 1355.843 **Åwith** the same uncertainty. In both sets of spectra, line intensities of these two lines, like those of other carbon lines nearby, generally follow the pattern of gf values, but not linearly. Thus the solar VUV data consistently place the **2p4d** $^1F_3$ level at 83947.5 cm-l with an uncertainty of about 0.2 cm-l , in agreement with **Johansson's** 83947.43 cm-l with an implicit uncertainty of 0.5 cm-l .

As mentioned previously, **Johansson** could not find the emission line 3p $^1D_2$-4d $^1F_3$, calculated at 8818.48 **Å.** Recent accurate multi-configuration relativistic calculations by **Hibbert** ***et al.*** [10] revealed that the gf value for this transition was only 0.0011, and hence too weak to be observed in **Johansson's** emission experiment. For comparison, the calculated gf value is 5.3 for the first line in Table VI, with the same 4d $^1F_3$ as the upper level. From **Johansson's** energy levels, this **IR** line is expected to be at 2177.64 cm-l , which falls in the region of a CO fundamental band, whose line depths are observed in absorption to be more than an order of magnitude larger than the estimated depth of the carbon line. Our estimated depth of 1.1 is made from the unblended line originating from the same lower level at 2107.557 cm-l in Tables 1. Since there are no unidentified lines of significant strength (1 % depth) within a couple of cm^{-1} of the calculated position, we assume that this line is blended or that the VUV data are somehow less accurate than stated.

In any event, it appears that the 4d $^1F_3$ level has to be determined through transitions with it as the lower level. Selection rules limit these transitions to 2 series, np $^1D_2$ and the nf series. Unfortunately, the accurate calculations of **Hibbert** ***et*** al. do not cover these transitions, so we have to resort to less accurate calculations. Table VI gives the calculated gf values of the strongest transitions from Victor and **Escalante** (VE) [19]; for the 4d-5f transitions, we use the scaling described in Sec.IIIC. Although the transition to 5p $^1D_2$ has a reasonably large gf of 2.3, it falls in the 7 micron region where the CF=0.01. As expected, this line is not observed as indicated in Table VI.

Since the position of the 4d $^1F_3$ level is not known well, we could postulate that the closest unidentified line with the expected depth be the 4p $^1D_2$-4d $^1F_3$ transition. In the *A TMOS* spect ra, a suitable candidate is the line at 2182.680 cm-l and a depth of 1.5, placing the level at 83952.543 cm-l . Remarkably, Table VI shows that all 6 transitions (including one blend) arising from the 4d $^1F_3$ level emerge in the spectra close to the appropriate wavenumbers. However, raising this level by 5 cm-l as suggested by the IR data would render the two transitions from the ground configuration incompatible with the VUV spectra. Besides, examination of the gf values in Table VI reveals that they do not correlate well with the observed intensities. We recall that for the 4d-5f array CF=0.15. Therefore, the 4 lines with gf less than 0.4 should have intensities below 0.1 and hence unobservable. So the good agreement between their observed and calculated (using the revised) waveneumbers are mere fortuitous coincidences. Of the remaining two lines, one has the predicted intensity, but its observed wavenumber deviates from the calculated by more than 0.1 cm-l . The other, which agrees well in wavenumber, is primarily due to the silicon line (blend), as the observed intensity is 5 times the predicted. Thus we are compelled to ignore the above 6 coincidences in wavenumbers and dismiss the proposal for the new position of the 4d $^1F_3$ level.

In that event, we must return to Johansson's identification of the 4d $^1F_3$ level, and investigate whether its position and the gf values of IR lines involving this level are consistent with the spectra. Since 3 lines in Table VI have predicted intensity above the observational limit of 0.1, we list only these three transitions and their predicted intensities in Table VII. In each block, the first column is the proposed position of the 4d $^1F_3$ level, followed by the wavenumbers for the 3 transitions calculated from our revised levels in Table IV. The next line shows the closest observed lines with their intensities. In the case of Johansson's value (labeled J), two of the three observed intensities are significantly below the predicted values and the last line seems rather discrepant, so we turn to other candidates. For the other 4 entries, the proposed positions for 4d $^1F_3$ level are determined from the average of the 3 observed transitions listed with the observed intensities. The first and the last blocks are rather unlikely candidates, because the departure from the **Johansson** value are about 3 times the Standard deviation and the observed intensities of 0.1 in both cases are 3 times smaller than the predicted value. It is difficult to choose between the remaining 2 candidates, but we favor the third entry since it is closer to the **Johansson** value and the intensity of the first line is more than adaquate whereas the corresponding value of the second entry is somewhat inadequate to account for the blends. With this choice, the 4d $^1F_3$ level is determined by only one weak unblended line, supported by two blended lines. Therefore, its uncertainty is as large **as** 0.02 cm-l .

IV. HIGH EXCITATION AND NEW LEVELS

As our primary goal, we now present data for new levels not **in** Moore's compilation [4]. The new levels are either high ℓ, the orbital quantum number and low n, ***or*** vice versa, As mentioned in **Sec.I,** our high ℓ levels are mostly different from those identified by **Geller** [8]. However, our high n levels are essentially the ones identified by Feldman ***et al.*** [14], **with** slight improvements, including 2 additional levels ***from*** other VUV data.

A. High ℓ Rydberg States

Theory for the high ℓ Rydberg levels has been extensively developed in the case of neon [23], and will not be repeated here. The main parameters in that theory are the ionic core splitting ($^2P_{1/2} - ^2P_{3/2}$, normal in carbon and inverted in neon) δE, the quadruple moment Q and the **polarizability** α_S. With a tunable far-infrared laser, Cooksy ***et*** al. [24] have meaaured δE to be 63.3951(1) cm-l . Using Doppler-tuned $C0_2$ laser spectroscopy of high ℓ Rydberg-Rydberg transitions in carbon, Ward and Lundeen [12] found Q= O.475(2) ea_o^2 and $\alpha_S=5.48(2)\, a_o^3$. These values represent significant improvement over those in an earlier work [11] of 0.515 ea_o^2 and 5.72 a_o^3 respectively, used by **Geller** to calculate and identify the high ℓ levels [8].

With these improved core parameters, we calculate the 5g and **5g′** (and other high ℓ) levels in the **jK** represention, and use these in column 2 of Tables 1-111. The results are expected to be accurate to 0.1 cm-l , excluding the uncertainty of 0.1 cm-l in the ionization limit of **Johansson.** As in **Geller's** work, we identify the 4f-5g (and **4f'-5g')** lines by seeking pairs of lines separated by the observed 4f pair splitting, and within 0.3 cm^{-1} of the calculated **wavenumbers.** In addition, we impose the maximum value of CF=O. 15 from the 4d-5f array, which has a lower excitation energy (and about the same frequency), This process enables us to find the **4f-5g** lines shown in Table L Remarkably, each pair of lines yields a 5g or 5g' level consistent to about 0.01 cm-* , hence we can produce the observed levels given in Table IV. However, our identifications differ from those given by **Geller** [8], except for the two lines at 2476.223 and 2476.365 cm-l . Note that we have changed the identification of the line at 2478.978 cm-l , so it appears in both Tables I and 111 with the new and the old labeling respectively. The difference bet ween the two sets of lines is only a few tenths of 1 cm-l , but the present is consistently **closer** to the theoretical values. Further, the intensity of the present set ranges from 0.3 to 1.8, whereas **Geller's** ranges from 1.6 to 5.4. While he did not have gf values to relate to the intensities, the lower intensities are consistent with the upper limit imposed by the product of our calculated gf values and **CF=0.15**: **Geller** could not find the two weakest lines, but we are able to account for them at 2462.02 and 2462.13 (blended) cm-l . Finally **Geller's** identifications lead to somewhat discrepant 5g or 5g' levels, whereas ours do not as noted above. The pair splitting of the 5g levels is estimated to be a few **mK** and undetectable in the present data, so we treat the pair as a single level and drop the J designation. The accuracy of the 5g levels is about 10 mK.

Using theoretical values for the 6h levels, we search for the 5g-6h lines, which are expected to be considerably weaker than the **4f-5g** lines owing to the higher excitation energy. Further, at 7 microns in the solar spectra, these lines are formed at a even lower temperature than the 4 micron lines. We have found the expected 6 lines displayed in Table I, with intensities near the noise limit (0.1), and within a discrepancy of 0.06 cm-l with theory. Again, they are different from **Geller's** identification of two of these lines, whose intensities are about an order of magnitude greater, and whose discrepancies with theory are 5 times larger. Our identification of the 5g-6h array suggests that the line intensities are approximately 0.01 times the gf values. Hence lines with gf values under ten (e.g. **n=5-6** low ℓ transitions) in this spectral regime are too weak to be observed. So a few near coincidences are moved from Table I to Table 111.

Similar to the 5g-6h lines, the 5f-6g lines appear to be present, but are even weaker in accordance with theory. Table I shows 6 of the expected 11 lines (two are blended); the rest are too weak to be observed. Once more, we cannot confirm the 2 identifications by Geller, as those lines are too strong and are discrepant with theory by about 0.2 cm-l . We attempt to confirm the above identification of the 6g levels through the 4f-6g transitions, but fail to find any lines in this array. Our finding is consistent with the theoretical prediction that these lines are almost an order of magnitude weaker than the 5f-6g lines, which are barely detectable. Thus we discount the three 4f-6g lines identified by Geller in these data, and relegate them to Table III.

B. High n Rydberg levels

From their VUV solar flare spectrum, Feldman *et* al. [14] have determined 63 new levels in carbon. The lines are mostly in emission from nd (up to n=29) levels to the ground configuration. Since the wavelength accuracy is about 0.004 Å, the the energy levels have been given to only one decimal place.

Taking advantage of all available data, we combine theirs with the solar data of Sandlin *et al.* [15] and Kelly's compilation [13] from laboratory data. For a typical nd level, which is determined by the average of 3 lines, the statistical error is about 0.08 cm-l , so it is given to 2 decimal places in Table IV. The values of our levels generally agree to 0.2 cm-l with Feldman *et al.* 's. One exception is the 16d $^3F_3$ level, where our value is 5 cm^{-1} below theirs. Their position is given as coincidental with the 15d $^1F_3$ level, since both are found by the same blended line. Ours is based on the Sandlin *et al.* identification of a new line at a longer wavelength by 0.08 Å, which is absent in the Feldman spectrum. We have also re-assigned their 24d $^1F_3$ level (quantum defect $\mu = 0.217$) to the 29d $^3F_3$ level ($\mu = 0.013$), since μ for other levels are less than 0.1 in both series. From Kelly's line list, it appears that one could find 9 more new levels using other VUV lines, not present in Feldman's spectrum. However, closer scrutiny reveals that the underlying lines are mostly from Johansson's *calculated* values. These seemed to be quoted for unresolved line wavelengths by Junkes *et al.*

[2], as Johansson listed these levels as extrapolated. Nevertheless, there are two exceptions, where the wavelengths actually differ, so the values from Junkes *et al.* must have been independently measured, From these values, we obtain 2 new levels: 7d $^3P_0$ and 8d $^3F_2$, where in the latter case, we have averaged in the wavelength from Paschen and Kruger [22].

V. IONIZATION POTENTIAL

Johansson has determined the ionization potential by extrapolating the np $^3D_3$ series to the ionic 2p $^2P_{\frac{3}{2}}$ limit. As it turns out, our modification of the 3p and 4p levels are less than 10 mK and inconsequential, resulting in no change for his three-term quantum defect formula for this series. Using this quantum defect for each known member (up ton= 10), we calculate its term value and add to the energy level in Table IV to obtain a value for the limit. The statistical average of these limits is **90883.854±0.015** cm-l , which is only 14 mK above Johansson's value, Taking the precise value of the ionic ground state splitting from Cooksy *et* al. [24], we find the ionization potential (2p $^2P_{\frac{1}{2}}$ limit) to be **90820.469±0.015** cm-l . Our value is 39 mK above Johansson's, which is well within his uncertainty of 100 mK.

The ionization potential can also be evaluated from the high ℓ Rydberg levels in a similar manner. Summing the calculated term values as described in Sec. IIID and the levels in Table IV, we obtain a value for each of the 5g, 6g, and 6h levels, The statistical average is **90820.38±0.12** cm-l , which is far less accurate but compatible with the value above.

In principle, the long nd $^1F_3$ and $^3F_3$ series can yield an accurate value for the ionization potential. However, they mutually perturb each other as the adjacent member spacing becomes less than the difference of their respective series limit (given by δE) as n exceeds 14. The series have been analyzed by multichannel quantum defect theory, but no value for the ionization potential has been given by Feldman *et* al. [14].

VI. CONCLUSIONS

We have analyzed all available spectral data on carbon to determine accurate experimental values of the energy levels given in Tbble IV. In the solar infrared spectra, we have identified 181 lines as belonging to C I. Our procedure requires the observed line intensity to match calculated gf values and a conversion factor, which can be estimated from other securely identified lines originating from the same level (or from others with nearly the same excitation energy), Consequently, a rather large number of lines, 59, have been rejected as accidental coincidences, mostly because their estimated intensity is not expected to contribute significantly to the observed line or that it is below the observational limit, A true test may be conducted by carrying out a radiative transfer computation with the PANDORA program of the Harvard-Smithsonian VAL solar atmosphere model [18].

We have improved the accuracy of the term system in Johansson's classic work on carbon by an order of magnitude, and found 19 new levels, as indicated in column 4 of Table IV. They belong mostly to high $\ell(\geq 4)$ levels, which have been calculated with core parameters derived from high precision laboratory measurements [12] with 10 micron $C0_2$ lasers. Our work is also facilitated by the very high precision FIR laser measurements of the fine structure splittings in both the neutral [7] and the ionic [24] ground states. Included in Table IV are the 63 levels found by Feldman *et al.* with minor modifications and the addition of 10 more levels from VUV lines. Thus this work demonstrates the importance of utilizing spectra from all wavelengths and from all sources, laboratory and solar.

At the outset, we expect to greatly improve the accuracy of the reclusive 4d $^1F_3$ level through several IR lines in the 4 micron region. Unfortunately, they fall near the bandhead of a strong CO fundamental band or are blended with other solar lines. So line identifications leading to this level are not unambiguous as depicted in various scenarios summarized in Tables VI and VII. A possible resolution has been proposed [25] to measure accurately both the VUV transitions with multiphoton spectroscopy and the IR transitions with laser frequency difference methods.

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Tables for:

Improved Experimental and Theoretical Energy levels of Carbon I

Chang & **Geller**

1. Table 1. **Transitions** 1300-4800 $\mathbf{cm^{-1}}$ **in** the *ATMOS* spectra
2. Table 2. Transitions 4700-5700 $\mathbf{cm^{-1}}$ **in** the *MARK IV* spectra
3. Table 3. Coincidental lines not belonging to carbon
4. Table 4. New Energy Levels
5. Table 5. gf values for the 3d-4f transition array
6. Table 6. Coincidental Transitions with 4d $^1F_3$ shifted **by** 5 cm-l
7. Table 7. New Values for the 4d $^1F_3$ level

Table 1: C I **Transitions** from the ATMOS spectra 2-16 μm

Ohs, **Wvnmbr**	**Calc.**	Designation	Inten.	**gf**	Comment
1338.716	.663	$5g'[2\frac{1}{2}] - 6h'[3\frac{1}{2}]$	0.1b	21	narrow, **CO**
1339.013	.04	$5f'[1\frac{1}{2}]_2 - 6g'[2\frac{1}{2}]$	0.2	5.9	new 5f
1341.199*	.232	$5g'[5\frac{1}{2}] - 6h'[6\frac{1}{2}]$	0.1	40	
1344.11	.161	$5g[4\frac{1}{2}] - 6h[5\frac{1}{2}]$	0.2	34	
1344.332	.396	$5g'[3\frac{1}{2}] - 6h'[4\frac{1}{2}]$	0.3	26	
1344.567	.624	$5g[3\frac{1}{2}] - 6h[4\frac{1}{2}]$	0.2	28	
1347.50	.428	$5g'[4\frac{1}{2}] - 6h'[5\frac{1}{2}]$	0.1	33	
1347.773	.79	$5f'[4\frac{1}{2}] - 6g'[5\frac{1}{2}]$	0.2	29	new 5f, pair
1349.731	.77	$5f'[2\frac{1}{2}] - 6g'[3\frac{1}{2}]$	0.1b	13	new **5f,** pair
1355.422	.42	$5f[3\frac{1}{2}]_4 - 6g[4\frac{1}{2}]$	0.1b	10	
1360.858	.81	$5f'[3\frac{1}{2}]_3 - 6g'[4\frac{1}{2}]$	0.1b	8.0	
1831.61	.58	$3d\ ^1P_1 - 4p\ ^1P_1$	0.1b	0.7	
1902.27	.25	$4d\ ^1D_2 - 5p\ ^1D_2$	1.9b	0.3U	
1992.266	.23	$3d\ ^3P_1 - 4p\ ^3P_0$	0.2	0.21	,
2002.620	.60	$3d\ ^3P_0 - 4p\ ^3P_1$	0.5	0.23	,
2014.90	.91	$3d\ ^3P_2 - 4p\ ^3P_1$	0.4b	0.24	
2025.22	.21	$3d\ ^3P_1 - 4p\ ^3P_2$	0.6bs	0.27	
2033.143	.14	$3d\ ^3P_2 - 4p\ ^3P_2$	18.7b	0.89	
2107.557	.52	$4p\ ^1D_2 - 5S\ ^1P_1$	0.3	1.6	un
2222.587*	.57	$4s\ ^1P_1 - 4p\ ^1P_1$	0.5	0.55	
2377.285	.33	$4d\ ^3P_0 - 5f'[1\frac{1}{2}]_1$	0.7bs	0.87	VE
2379.549*	.56	$4d\ ^3P_2 - 5f'[2\frac{1}{2}]_3$	0.5	3.17	un
2379.663*	.68	$4d\ ^3P_2 - 5f'[2\frac{1}{2}]_2$	0.3b	0.24	VE
2382.633*	.55	$4d\ ^3P_1 - 5f'[1\frac{1}{2}]_2$	0.2	1.17	VE
2408.388	.37	$4p\ ^3P_2 - 5s\ ^3P_1$	0.1	0.15	
2447.031*	.05	$4p\ ^3P_2 - 5s\ ^3P_2$	0.4	0.59	
2450.65	.63	$4d\ ^1P_1 - 5f'[2\frac{1}{2}]_2$	0.1	1.40	VE
2462.020	.016	$4f'[1\frac{1}{2}]_2 - 5g'[2\frac{1}{2}]$	0.4	6.7	
2462, 125*	.126	$4f'[1\frac{1}{2}]_1 - 5g'[2\frac{1}{2}]$	0.3	4.0	
2466.612	.49	$4d\ ^1P_1 - 5f'[1\frac{1}{2}]_2$	6.7b	1.13	mainly Si
2476.216*	.36	$4f'[2\frac{1}{2}]_2 - 5g'[3\frac{1}{2}]$	2.3b	6.0	
2476.365	.51	$4f'[2\frac{1}{2}]_3 - 5g'[3\frac{1}{2}]$	1.6bs	8.4	
2478.590*	.75	$4f'[4\frac{1}{2}]_4 - 5g'[5\frac{1}{2}]$	1.8	11.3	
2478.978*	9.14	$4f'[4\frac{1}{2}]_5 - 5g'[5\frac{1}{2}]$	2.5	13.8	

2494.073*	.09	$4p\ ^3P_2 - 4d\ ^3D_2$	0.9	.37	
2494.386*	.37	$4\ p\ ^3P_1 - 4\ d\ ^3D_1$	1.2	.59	
2499.2(I8*	.41	$4f'[3\frac{1}{2}]_4 - 5g'[4\frac{1}{2}]$	1.8b	10.8	
2499.522*	.64	$4f'[3\frac{1}{2}]_3 - 5g'[4\frac{1}{2}]$	1.3b	8.4	
2501,14	.082	$4f[3\frac{1}{2}]_4 - 5g[4\frac{1}{2}]$	1bs	11.8	
2501.250*	.189	$4f[3\frac{1}{2}]_3 - 5g[4\frac{1}{2}]$	1.1b	9.1	
2504,803	.84	$4p\ ^3P_2 - 4d\ ^3D_3$	2.0	3.77	
2507.260	.189	$4f[2\frac{1}{2}]_2 - 5g[3\frac{1}{2}]$	0.8bs	6.7	
2507.367	.299	$4f[2\frac{1}{2}]_3 - 5g[3\frac{1}{2}]$	1.1	9.1	
2509.160	.12	$4p\ ^3P_0 - 4d\ ^3D_1$	3b	1.02	
2512,395	.32	$4p\ ^3P_1 - 4d\ ^3D_2$	10.7b	2,41	
2516.355*	.36	$3d\ ^3D_3 - 4p\ ^3D_3$	0.7	.36	
2565.858	.86	$4d\ ^3D_3 - 5f[3\frac{1}{2}]_4$	0.7b	2.71	
2576.50	.41	$4d\ ^3D_2 - 5f[3\frac{1}{2}]_3$	1bs	0.92	VE
2583.360*	.44	$3d\ ^3F_2 - 4p\ ^3D_1$	1.4	.78	
2584.660	.67	$3d\ ^3F_4 - 4p\ ^3D_3$	2.0	1.63	
2585.76	.76	$3d\ ^3F_3 - 4p\ ^3D_2$	1s	1.17	
2591.987	.92	$4d\ ^3D_1 - 5f[2\frac{1}{2}]_2$	1.4b	2.20	VE
2602.200	.20	$3d\ ^3F_2 - 4p\ ^3D_2$	0.1	.12	
2619.137	.10	$3d\ ^3F_3 - 4p\ ^3D_3$	0.8b	0.07	.
2620.927	.83	$4d\ ^3D_3 - 5f'[3\frac{1}{2}]_4$	1.5b	1.84	VE
2631.462	.43	$4d$ ‘$D_2 - 5f'[3\frac{1}{2}]_3$	0.2b	0.78	VE
2635.09	.03	$4p\ ^3S_1 - 58\ ^3P_0$	lb	0.29	
2647.375*	.38	$4p\ ^3S_1 - 5s\ ^3P_1$	0.6	0.85	
2653.184*	.18	$4s\ ^3P_2 - 4p\ ^3D_2$	1.0	.46	
2653.463	.43	$4d\ ^3F_3 - 5f[3\frac{1}{2}]_4$	0.5	2.28	VE, un
2665.693	.77	$4s\ ^3P_1 - 4p\ ^3D_1$	0.8	.46	
2667.116	.10	$4d$ ‘$F_a - 5f[3\frac{1}{2}]_3$	0.4	1.60	VE, un
2677.458	.53	$48\ ^3P_0 - 4p\ ^3D_1$	1.1b	.68	
2684.519	.53	$4s\ ^3P_1 - 4p\ ^3D_2$	2.6	1.50	
2686.023	.01	$4p\ ^3S_1 - 5s\ ^3P_2$	1.2	1.46	
2686.518	.52	$4s\ ^3P_2 - 4p\ ^3D_3$	3.6	2.26	
2689.415	.42	$4d\ ^3F_4 - 5f'[4\frac{1}{2}]_5$	1.2	6.77	VE, pair
2708.537	.40	$4d\ ^3F_3 - 5f'[3\frac{1}{2}]_4$	0.3b	1.49	VE
2722.100	.12	$4d\ ^2F_2 - 5f'[3\frac{1}{2}]_3$	0.3	2.34	VE
2726.720	.73	$4d\ ^3F_3 - 5f'[4\frac{1}{2}]_4$	0.3	1.65	VE
2759.077	.11	$4p\ ^3P_2 - 4d\ ^3P_2$	1.7	2.14	
2772.070*	.10	$4p\ ^3P_2 - 4d\ ^3P_1$	0.3	0.62	

2777.335*	.34	4p $^3P_1$ - 4d $^3P_2$	0.2b	0.34	
2790.326	.33	4p $^3P_1$ - 4d $^3P_1$	0.5	0.54	
2795.479*	.46	4p $^3P_1$ - 4d $^3P_0$	0.8b?	0.55	
2805.08	.08	4p $^3P_0$ - 4d $^3P_1$	0.3	0,42	
2883.057	.03	3d $^1D_2$ – 4p $^1P_1$	1.8	0.637	
2914.389*	.36	4d $^1D_2$ – 5f $[2\frac{1}{2}]_3$	0.4	1.39	VE
2916.836	.87	4d $^1D_2$ - 5f $[3\frac{1}{2}]_3$	2b	1.43	VE, mostly Fe
2926.655*	.65	4p $^3D_3$ – 4d ^3F 3	0.6	.235	
2934.697	.77	4p $^1P_1$ – 4d $^1D_2$	3.6	2.86	
2946.129	.12	4p $^3D_2$ – 4d $^3F_2$	0.5	0.33	
2951.147	.14	4p $^3D_2$ – 5s $^3P_1$	1.4	1.01	
2956.457*	.43	4p $^3D_3$ – 5s $^3P_2$	2,2	1.65	
2956.961	.94	4s $^3P_2$ -4p $^3S_1$	3.2b	1.03	
2957.640*	.55	4p $^3D_1$ – 5s $^3P_0$	1.2	0.49	
2959.982	.99	4p $^3D_2$ – 4d ^3F 3	4.9	4.95	
2963.980	.96	4p $^3D_3$ – 4d $^3F_4$	6.0	7.00	
2964.976*	.88	4p $^3D_1$ – 4d $^3F_2$	4.1	3.45	
2969.982*	.90	4p $^3D_1$ – 5s $^3P_1$	0.6	0.37	
2971.97	.89	4d $^1D_2$ - 5f' $[3\frac{1}{2}]_3$	0.4bs	0.46	VE ‘
2988.296*	.29	4s $^3P_1$ – 4p $^3S_1$	2.1b	0.76	.
2989.792*	.77	4p $^3D_2$ – 5s $^3P_2$	0.9	0.60	
2998.065*	.07	4p $^3S_1$ - 4d $^3P_2$	1.5d	1.25	
3000.069	.05	4s $^3P_0$ – 4p $^3S_1$	0.9	0.28	
3003.450*	.47	4p $^3D_3$ – 4d $^3D_2$	0.7b	0.48	
3011.050	.06	4p $^3S_1$ – 4d $^3P_1$	0.7s	0.64	
3014.237*	.22	4p $^3D3$ – 4d $^3D3$	2.2	1.54	
3016.123*	.19	4p $^3S_1$ - 4d $^3P_0$	0.4b	0.20	
3017.551*	.52	3d $^3D_1$ – 4p $^3P_0$	0.6	0.23	
3018.16	.13	3d $^3D_2$ – 4p $^3P_1$	1.6b	0.56	‘
3018.853*	.86	4p $^3D_2$ – 4d $^3D_1$	0.1	0.16	
3025.794	.74	3d $^3D_3$ – 4p $^3P_2$	2.4	0.91	double
3032.300	.27	3d $^3D_1$ – 4p $^3P_1$	0.3b	0.15	
3036.403*	.36	3d $^3D_2$ – 4p $^3P_2$	0.3	0.11	
3036.795	.81	4p $^3D_2$ – 4d $^3D_2$	b	0.59	
3037.676*	.62	4p $^3D_1$ – 4d $^3D_1$	0.1	0.33	
3038.586*	.52	3d $^1P_1$ – 4p $^1D_2$	0.2	0.44	
3177.709	.67	4s $^3P_2$ – 4p $^3P_1$	1.7	0.43	
3194.284	.27	4s $^3P_1$ – 4p $^3P_0$	3.4b	0.27	
3195.955*	.90	4s $^3P_2$ – 4p $^3P_2$	3.5	1.14	

3209.053*	.02	4s $^3P_1 - 4p\ ^3P_1$	1.1s	0.17	
3220.825*	.78	4s $^3P_0 - 4p\ ^3P_1$	1.4b	0.22	
3227.292*	.25	4s $^3P_1 - 4p\ ^3P_2$	1.4s	0.32	
3240.23	.17	3d $^1F_3 - 4p\ ^1D_2$	0.5	0.55	
3314.57	.547	4p $^1P_1$ - 5s $^1P_1$	0.1	0.69	V E
3429.575*	.51	4s $^1P_1 - 4p\ ^1D_2$	6.3	2.20	
3469.249*	.30	4p $^1P_1 - 4d\ ^1P_1$	2.6	1.36	
3476.373*	.30	3d $^3D_1$ - 4p $^1D_2$	0.3g	0.16	ic
3520.432	.44	3d $^1P_1 - 4p\ ^1S_0$	16b	0.015	
3868.589	.58"	3p $^3P_2 - 2p^3\ ^3P_1$	2+	0.089	
3869.882	.86"	3p $^3P_2 - 2p^3\ ^3P_2$	7.5	0.271	
3889.071	.08'	3p $^3P_1 - 2p^3\ ^3P_1$	3	0.056	
3890.363	.36"	3p $^3P_1 - 2p^3\ ^3P_2$	4	0.088	
3891.239	.22	3p $^3P_1 - 2p^3\ ^3P_0$	4	0.074	
3901.467	.46	3p $^3P_0 - 2p^3\ ^3P_1$	3.3b	0.073	
3911.393*	.43	4s $^1P_1 - 4p\ ^1S_0$	1.5bs	.68	
4090.055	.05	3d $^1D_2 - 4p\ ^1D_2$	1.2bs	0.162	
4317.590*	.58	3p $^1S_0 - 3d\ ^3D_1$	1.7	0.065	ic
4364.376	.37"	3p $^1S_0 - 4s\ ^1P_1$	9.3	0.6441	
4510.030*	.02	3p $^3S_1 - 2p^3\ ^3P_1$	1.1	0.013	
4511.329*	.32	3p $^3S_1 - 2p^3\ ^3P_2$	2.4	0.031	
4512.207*	.17	3p $^3S_1 - 2p^3\ ^3P_0$	0.5	0.004	
4600.979*	.98	3d $^3P_1 - 4f\ [2\frac{1}{2}]_2$	0.3b	0.073	
4608.782*	.80	3d $^3P_2 - 4f\ [2\frac{1}{2}]_3$	2.3b	0.35	
4694.6(I7*	.60[a]	3d $^3P_1 - 4f'[2\frac{1}{2}]_2$	4.1b	0.67	
4702.396*	.41[a]	3d ‘$P_a - 4f'[2\frac{1}{2}]_3$	10.6	3.05	
4702.54	.55	3d $^3P_2 - 4f'[2\frac{1}{2}]_2$	bs	0.23	
4713.131*	.13"	3d $^3P_0 - 4f'[1\frac{1}{2}]_1$	10.6	0.84	
4717.542*	.51	3d $^3P_1 - 4f'[1\frac{1}{2}]_1$	5b	0.64	
4717.64	.61"	3d $^3P_1 - 4f'[1\frac{1}{2}]_2$	6b	1.12	
4725.485*	.46	3d $^3P_2 - 4f'[1\frac{1}{2}]_1$	lb	0.04	
4725.573*	.55	3d $^3P_2 - 4f'[1\frac{1}{2}]_2$	2b	0.37	
4755.368*	.37"	3p $^1S_0 - 3d\ ^1P_1$	8	0.352	

*= fitted line center; a=JL [?]: b=blend; s=shoulder; g=satellite gas; ic=intercombination; un=unusual shape; VE=Victor and Escalante [?]

Table 2: **C** I **Transitions** from the *MARK IV* spectra 4700-5700 cm^{-1}

Obs.Wvnmbr	**Calc.**	Designation	**Inten.**	**gf**
4702.398	.41[a]	$3d\ ^3P_2 - 4f'[2\frac{1}{2}]_3$	11.0	3.05
4702.56	.55	$3d\ ^3P_2 - 4f'[2\frac{1}{2}]_2$	*bs*	*0.23*
4713.133	.13[a]	$3d\ ^3P_0 - 4f'[1\frac{1}{2}]_1$	*5.3*	*0.84*
4717.52	*.51*	$3d\ ^3P_1 - 4f'[1\frac{1}{2}]_1$	*s*	*0.64*
4717.634	*.61”*	$3d\ ^3P_1 - 4f'[1\frac{1}{2}]_2$	*6.2*	*1.12*
4725.46	*.51*	$3d\ ^3P_2 - 4f'[1\frac{1}{2}]_1$	*s*	0.04
4725.576	.55	$3d\ ^3P_2 - 4f'[1\frac{1}{2}]_2$	**2.8** ,	0.37
4755.366	.37[a]	$3p\ ^1S_0 - 3d\ ^1P_1$	9.5	, 0.35
5069.102	.10[a]	$3p\ ^1D_2 - 3d\ ^1D_2$	*bs*	*0.557*
5188.50	*.49*	$3d\ ^1P_1 - 4f[2\frac{1}{2}]_2$	*b – Atm*	*0.12*
5282.127	.14[a]	$3d\ ^1P_1 - 4f'[2\frac{1}{2}]_2$	10.1	1.33
5305.148	.16[a]	$3d\ ^1P_1 - 4f'[1\frac{1}{2}]_2$	7.6	1.08
5390.016	.03	$3d\ ^1F_3 - 4f[2\frac{1}{2}]_3$	3.0	0.20
5456.846	.83[a]	$3d\ ^1F_3 - 4f'[3\frac{1}{2}]_4$	10.4	1.91
5483.602	.63	$3d\ ^1F_3 - 4f'[2\frac{1}{2}]_3$	2.0	0.05
5486.620	.64[a]	$3d\ ^1F_3 - 4f'[4\frac{1}{2}]_4$	15.4	4.34
5511.237	.24”	$3p\ ^3D_3 - 2p^3\ ^3P_2$	*8.9*	*0.12*
5526.301	*.39*	$2p^3\ ^3P_0 - 4p\ ^3D_1$	*10.7b*	*0.084*
5528.469	*.54*	$2p^3\ ^3P_1 - 4p\ ^3D_1$	*2.6*	*0.056*

5543.310	.30"	3p $^3D_2 - 2p^3\,^3P_1$	7.4	0.068
5544.599	.65"	3p $^3D_2$ - $2p^3\,^3P_2$	4.5b	0.019
5545.993	6.00	$2p^3\,^3P_2 -$ 4p $^3D_2$	2.3	0.050
5547.312	.30	$2p^3\,^3P_1$ - 4p $^3D_2$	8.5	0.187
5564.425	.51[a]	3p $^3D_1 - 2p^3\,^3P_1$	5.7b	0.021
5566.659	.64[4]	3p $^3D_1 - 2p^3\,^3P_0$	4.7	0.030
5579.332	.34°	$2p^3\,^3P_2 -$ 4p $^3D_3$	9.3	0.327
5598.496	.53	$2p^3\,^3D_2$ -3p $^3D_1$	2.2	0.0014
5599.604	.63	$2p^3\,^3D_1 -$ 3p $^3D_1$	2.9	0.0038
5601.399	.40	3d $^3D_3 - 4f\,[2\frac{1}{2}]_3$	2.7	0.076
5608.151	.15[a]	3d $^3D_3$ - $4f\,[3\frac{1}{2}]_4$	16.9b	3.17
5612.023	.02"	3d $^3D_2 - 4f\,[2\frac{1}{2}]_3$	14.2	2.00
5618.590	.57	3d '$D_a - 4f\,[3\frac{1}{2}]_3$	9.7b	0.88
5619.700	.71	$2p^3\,^3D_2 -$ 3p $^3D_2$	3.9	0.0058
5620.819	.81	$2p^3\,^3D_1 -$ 3p $^3D_2$	3.1	0.0014
5623.708	.74	$2p^3\,^3D3 -$ 3p $^3D_2$	2.2	0.0015
5626.273	.26"	3d $^3D_1 - 4f\,[2\frac{1}{2}]_2$	14.7b	2.56
5657.088	.11	$2p^3\,^3D_3 -$ 3p $^3D_3$	9b	0.019
5668.217	.23"	3d $^3D_3 - 4f'[3\frac{1}{2}]_4$	15b	2.12
5678.58	.59	3d $^3D_2 - 4f'[3\frac{1}{2}]_3$	10	0.91
5694.97	5.00	3d $^3D_3 - 4f'[2\frac{1}{2}]_3$	3b	.90

a=JL [?]: b=blend; s=shoulder; g=satellite gas; Atm=atmospheric gaa

Table 3: Rejected observed lines coincidental with C I Transitions

Obs.Wvnmbr	Calc.	Designation	Inten.	gf	Comment
1342.194*	.19	5p $^3D_3 - 5d\ ^3F_3$	0.2	0.7	VE
1344.445	.161	$5g[4\frac{1}{2}] - 6h[5\frac{1}{2}]$	1.4	34	Gel
1344.858	.624	$5g[3\frac{1}{2}] - 6h[4\frac{1}{2}]$	1.3	28	Gel
1353.90	.91	$4d\ ^1D_2 - 5p\ ^1P_1$	1.4b	1.3	VE, Gel
1355.246	.42	$5f[3\frac{1}{2}]_4 - 6g[4\frac{1}{2}]$	1.0	10.4	Gel
1355.497	.42	$5f[3\frac{1}{2}]_3 - 6g[4\frac{1}{2}]$	1.2b	8.0	Gel
1376.769	.80	$5p\ ^3D_2 - 5d\ ^3F3$	0.1	5.8	VE
1382.276	.30	$5p\ ^3D_1 - 5d\ ^3F_2$	0.1	3.8	VE
1384.481	.50	$5p\ ^3D3 - 5d\ ^3F_4$	0.1	8.3	VE
1384.64	.63	$5p\ ^3D_3 - 6s\ ^3P_2$	0.1	2.8	VE
1459.26	.35	$3p\ ^3P_0 - 4d\ ^3D_1$	0.1	0.04	‘
1522.35	.39*	$5s\ ^1P_1 - 5p\ {}^*D_2$	0.1	3.5	‘ VE
1625.673	.60	$4p\ ^1S_0 - 5s\ ^1P_1$	6.3b	1.0	
1727.710	.83	$4p\ ^1D_2 - 4d\ ^1D_2$	3.1b	0.8	
2262.251	.36	$4p\ ^1D_2 - 4d\ ^1P_1$	4.3b	0.20	
2295.902	.96	$4d\ ^3P_1 - 5f[2\frac{1}{2}]_2$	0.5	0.06v	un
2450.986	1.01	$3d\ ^3P_1 - 4p\ ^1D_2$	3.4	2×10^{-3}	
2458.792	.94	$3d\ ^3P_2 - 4p\ ^1D_2$	0.4	9×10^{-4}	Gel
2478.988	.75	$4f'[4\frac{1}{2}]_4 - 5g'[5\frac{1}{2}]$	2.6	11.3	Gel
2479.418	.14	$4f'[4\frac{1}{2}]_5 - 5g'[5\frac{1}{2}]$	3.7	13.8	Gel
2483.100	.02	$3d\ ^3D_3 - 4p\ ^3D_2$	0.2	10^{-5}	
2483.100	.07	$4f'[1\frac{1}{2}]_2 - 5d\ ^3P_1$	0.2	.03	VE
2485.010	.02	$4f'[2\frac{1}{2}]_2 - 5g'[2\frac{1}{2}]$	0.4	0.12	
2493.465	.45	$4f'[2\frac{1}{2}]_3 - 5d\ ^3P_2$	0.4	.07	VE
2493.573	.64	$3d\ ^3D_2 - 4p\ ^3D_2$	0.6b	.156	blue sh
2499.102	.27	$4f'[3\frac{1}{2}]_4 - 5g'[4\frac{1}{2}]$	1.2bs	10.8	Gel
2499.358	.545	$4f'[3\frac{1}{2}]_3 - 5g'[4\frac{1}{2}]$	7.2	8.4	Gel

2500".609	.65	$4f\,[3\frac{1}{2}]_4 - 5g\,[3\frac{1}{2}]$	b	0.53	
2500.848	.82	$4f\,[3\frac{1}{2}]_3 - 5g\,[3\frac{1}{2}]$	1.2	0.41	
2500.95	1.082	$4f\,[3\frac{1}{2}]_4 - 5g\,[4\frac{1}{2}]$	6.1b	11.8	Gel
2500.98	1.189	$4f\,[3\frac{1}{2}]_3 - 5g\,[4\frac{1}{2}]$	6.1b	9.1	Gel
2503.178	.17	$4f'[3\frac{1}{2}]_4 - 5g'[3\frac{1}{2}]$	1.4	1.3	
2507.003	.189	$4f\,[2\frac{1}{2}]_2 - 5g\,[3\frac{1}{2}]$	5.4	6.7	Gel
2507.109	.299	$4f\,[2\frac{1}{2}]_3 - 5g\,[3\frac{1}{2}]$	2.0	9.1	Gel
2507.875	.78	$3d\,^3D_2 - 4p\,^3D_2$	0.8	.04	
2522.91	.82	$4f\,[3\frac{1}{2}]_4 - 5d\,^1F_3$	0.1	0.03	VE
2529.468	.43	$4f\,[2\frac{1}{2}]_2 - 5d\,^1F_3$	0.1	0.000	VE
2620.947	.94	$58\,^3P_2 - 5f\,[2\frac{1}{2}]_3$	1.5b	0.19	VE
2621.041	.01	$5s\,^3P_2 - 5f\,[2\frac{1}{2}]_2$	0.6	0.036	VE
2635.517	.54	$3d\,^3F_2 - 4p\,^3D_3$	b	6×10^{-4}	
2639.178	.13	$4d\,^3D_3 - 5f'\,[4\frac{1}{2}]_4$	0,2	0.14	VE
2659.562	.64	$58\,^3P_1 - 5f\,[2\frac{1}{2}]_2$	0.5	0.034	VE
2691.76	.74	$58\,^3P_2 - 5f'\,[2\frac{1}{2}]_2$	b	0.003	VE
2730.331	.37	$58\,^3P_1 - 5f'\,[2\frac{1}{2}]_2$	1.6b	0.048	VE
2746.10	.14	$58\,^3P_1 - 5f'\,[1\frac{1}{2}]_1$	b	0.050	VE
2746.23	.23	$5s\,^3P_1 - 5f'\,[1\frac{1}{2}]_2$	bs	0.14	VE
3008.493	.53	$3d\,^3D_1 - 5s\,^3P_2$	1.3	4×10^{-3}	
3102.720	.69	$3d\,^1D_2 - 4p\,^3D_1$	2.5b	0.04	ic
3462,147	.16	$3d\,^3D_2 - 4p\,^1D_2$	1.9b	5×10^{-5}	ic
3843.61	.77	$4f\,[3\frac{1}{2}]_4 - 6g\,[4\frac{1}{2}]$	2	1.6	Gel
3843.754	.94	$4f\,[3\frac{1}{2}]_3 - 6g\,[4\frac{1}{2}]$	4b	1.2	Gel
3850.561	.31	$4f\,[2\frac{1}{2}]_3 - 6g\,[3\frac{1}{2}]$	0.7	1.3	Gel
5530.367	.36	$4p\,^3D_2 - 6s\,^3P_1$	3.3	0.11	VE
5539.504	.43	$4p\,^3D_1 - 6s\,^3P_0$	1.1	0.05	VE
5588.400	.35	$3p\,^1D_2 - 3d\,^3F_2$	14.3b	0.0010	ic
5616.573	.56	$3d\,^3P_1 - 5p\,^3D_1$	2.9b	0.00002	
5631.62	.58	$3d\,^3P_1 - 5p\,^3D_2$	2.7	0.00006	
5674.15	.12	$3d\,^3P_2 - 5p\,^3D_3$	1	0.00017	
5676.21	.26	$3d\,^3F_4 - 4f\,[3\frac{1}{2}]_3$	9b	0.0038	
5682.69	.77	$3p\,^1D_2 - 3d\,^1D_1$	7b	0.081	ic
5696.92	.91	$3p\,^1D_2 - 3d\,^3D_2$	11b	0.0001	ic

b= blend: s=shoulder; Gel=in Geller [?]; ic=intercombination; un=unusual shape; VE=Victor and Escalante [?];

Table 4: Improved Carbon I Energy **Levels** 2pm?.

Designation	*J*	Level	Comment	**Intvl/Lines**
2p23P	*o*	*0.000*		
	1	16.417	***F***	16.41671
	2	43.414	***F***	26.9968
2p² ¹D	2	10192.670	***u***	4
2p21s	0	21648.035	***u***	3
2p3 ⁶s⁰	2	33735.214	***v***	2
3s 3P"	0	60333.428	***u***	1
	1	60352.619	***u***	3
	2	60393.165	***u***	2
3s *P°	1	61981.846	***u***	1
2p³3D"	3	64086.960	***M***	2
	2	64090.968	***M***	1
	1	64089.855	***M***	1 ,
3p ¹P	1	68856.366	***N***	**1**
3p 3D	1	69689.499	***M***	2
	2	69710.673	M	2
	3	69744.046	***M***	1
3p 3S	1	70743.953	***A***	2
3p 3P	0	71352.520	***A***	1
	1	71364.920	***A***	3
	2	71385.399	***A***	2
3p ¹D	2	72610.724	***M***	1
3p ¹S	0	73975.919	***A, V***	3,1
2p³ 3Po	2	75255.282	***A, U***	2,6
	1	75253.987	***A, U***	7,4
	0	75256.159	***A***	3
3d ¹D°	2	77679.825	***A***	1
48 ³P°	0	78104.983	***A***	4
	1	78116.755	***A***	6
	2	78148.096	***A***	4

3d $^3F^0$	2	78199.095	A	3
	3	78215.523	N	1
	4	78249.954	A	2
3d 3D0	1	78293.509	A	3
	2	78307.648	A	2
	3	78318.258	A	2
4s lP”	1	78340.298	A	l
3d $^1F^o$	3	78529.640	A	l
3d $^1P^o$	1	78731.287	A	2
3d $^3P^o$	2	79310.858	A	2
	1	79318.799	A	2
	0	79323.196	A	l
4p ^1P	1	80562.882	A	2
4p 3_D	1	80782.446	A	4
	2	80801.280	A	7
	3	80834.614	A	5
4p 3_s	1	81105.052	A	3
4p 3_P	0	81311.052	A	2
	1	81325.805	A	5
	2	81344.051	A	4
4p ^1D	2	81769.884	A	2
4p ^1S	0	82251.736	U	1
4d $^1D^o$	2	83497.579	A	2
5s $^3P^o$	0	83740.091	A	l
	1	83752.429	A	3
	2	83791.071	A	2
4d $^3F^o$	2	83747.422	A	2
	3	83761.256	A	3
	4	83798.594	A	l
4d 3D0	1	83820.127	A	2
	2	83838.067	A	3
	3	83848.851	A	l
5s $^1P^o$	1	83877.429	A	3
4f $[2\frac{1}{2}]$	3	83919.640	A, M	4
	2	83919.778	A	2

4*f* [3½]	3	83926.238	***M***	1
	4	83926.4X3	***M***	1
$4d\ ^1F^o$	3	83947.18	***A***	2
4*f*′ [3 ½]	***3***	***83986.228***	*M*	2
	4	***83986.488***	*M*	2
***4f’* [2½]**	***3***	***84013.254***	***A***	3
	2	***84013.406***	***A***	3
4*f*′ [4½]	***5***	***84015.874***	***N***	1
	4	***84016.262***	***M***	1
4*f*′ [1 ½]	**1**	84036.327	***A***	2
	2	84036.432	***A***	3
$4d\ ^1P^o$	**1**	84032.131	***A***	2
4d 3P”	2	84103.122	***A***	2
	1	84116.114	***A***	3
	0	84121.233	***u***	1
seeMoore				
5*f* [2½]	3	86411.968	***A***	1
	2	86412.07	***v***	1
5*f* [3½]	3	86414.538	***A***	**2**
	4	86414.73	***v***	**1**
5*f*′ [3+]	3	86469.522	***A***	2
	4	86469.790	***A***	3
5f’ **[2½]**	3	86482.671	***A***	1
	2	86482.785	***A***	1
5*f*′ [4+]	***5***	***86488.009***	***A, new***	1
	4	***86487.976***	***A, new***	3
5*f*′ [1 ½]	1	***86498.56***	***V***	1
	2	***86498.747***	***A***	1
5g [3 ½]°		***86427.03***	***A, new***	1
5g **[4½]°**		***86427.49***	***A, new***	1
5*g*′ [4½]°		***86485.72***	***A, new***	1
5g’ **[3½]°**		***86489.63***	***A, new***	1
5g’ **[5½]°**		***86494.85***	***A, new***	1
5*g*′ [2½]°		***86498.44***	***A, new***	1
6*g* [4½]°		***87770.15***	***A, new***	1
6g’ **[4½]°**		***87830.38***	***A, new***	1
6g’ **[3½]°**		***87832.45***	***A, new***	1
6*g*′ [5½]°		***87835.77***	***A, new***	1
6g’ **[2½]°**		***87837.76***	***A, new***	1

seeMoore

6h [5½]		87771.60	A, new	1
6h [4½]		87771.60	A, new	1
6h' [5½]		87833.06	A, new	1
6h' [4½]		87833.96	A, new	1
6h' [6½]		87836.05	A, new	1
6h' [3½]		87837.16	A, new	1
6d 3D	1	87735.31	U, Fel	4
6d ^3P	O	87846.89	U, new	1
7d 3_F	2	88541.45	U, new	1
7d 3_F	3	88544.90	U, Fel	4
7d 3_D	1	88558.65	U, Fel	5
7d 3_D	3	88606.33	U, Fel	3
7d 3_P	2	88636.83	U, new	1
7d ^3P	1	88646.10	U, Fel	5
7d 3_P	O	88649.10	U, new	1
8d 3_F	2	89079.95	U, new	1
8d 3_F	3	89082.15	U, Fel	4
8d 3_D	1	89091.83	U, Fel	2
8d 3_D	3	89144.01	U, Fel	2
8d 3_P	2	89162.19	U, new	1
8d 3_P	1	89170.07	U, Fel	2
9d 3_F	2	89447.46	U, new	1
9d 3_F	3	89449.60	U, Fel	3
9d 3D	1	89456.23	U, Fel	3
9d 3_D	3	89520.53	U, new	1
9d 3_P	2	89522.39	U, new	1
10s ^1P	1	89514.86	U, Fel	3
10d 3_F	3	89711.42	U, Fel	3
10d 3_D	1	89716.16	U, Fel	3
10d ^1F	3	89779.20	U, Fel	2
10d ^1P	1	89783.26	U, Fel	3
11d 3_F	3	89904.94	U, Fel	3
11d 3_D	1	89906.35	U, Fel	1
11d ^1F	3	89971.35	U, Fel	3
11d ^1P	1	89974.96	U, Fel	2
12d ^3F	3	90051.59	U, Fel	3
12d 3_D	1	90054.34	U, Fel	2
12d ^1F	3	90117.43	U, Fel	3
12d ^1P	1	90119.88	‘U, Fel	3

13s	^1P	1	90116.0	*U, Fel*	3
13d	^3F	3	90165.61	*U, Fel*	2
13d	^3D	1	90167.98	*U, Fel*	1
13d	^1F	3	90230.79	*U, Fel*	3
13d	^1P	1	90231.47	*U, Fel*	2
14s	^1P	1	90229.78	*U, Fel*	2
14d	^3F	3	90256.51	*U, Fel*	2
14d	^3D	1	90260.18	*U, Fel*	2
14d	^1F	3	90320.43	*U, Fel*	3
14d	^1P	1	90322.33	*U, Fel*	2
15d	^3F	3	90329.52	*U, Fel*	3
15d	^1F	3	90393.99	*U, Fel*	3
15d	^1P	1	90395.50	*U, Fel*	2
16d	^3F	3	90389.0	*U, new*	1
16d	^1F	3	90453.16	*U, Fel*	3
16d	^1P	1	90454.40	*U, Fel*	3
17d	^3F	3	90438.05	*U, Fel*	3
17d	^1F	3	90502.34	*U, Fel*	3
17d	^1P	1	90502.53	*U, Fel*	2
18d	^3F	3	90479.39	*U, Fel*	3
18d	^1F	3	90543.97	*U, Fel*	2
18d	^1P	1	90544.85	*U, Fel*	3
19d	^3F	3	90514.21	*U, Fel*	2
19d	^1F	3	90578.67	*U, Fel*	3
19d	^1P	1	90579.3	*U, Fel*	2
20d	^3F	3	90545.6	*U, Fel*	1
20d	^1F	3	90609.68	*U, Fel*	2
20d	^1P	1	90609.6	*U, Fe!*	3
21d	^3F	3	“90570.32	*U, Fel*	3
21d	^1F	3	90634.1	*U, Fel*	2
22d	^3F	3	90592.48	*U, Fel*	3
24d	^1F	3	90689.85	*U, Fel*	2
27d	^1F	3	90732.85	*U, Fel*	3
28d	^1F	3	90742.21	*U, Fel*	2
29d	^1F	3	90753.83	*U, Fel*	2

F=far infrared [?], U=VUV [?], V=visible(extended) [?],
M=Mark IV [?], N=near **IR** [?], A= ATMOS, **Fel=in** Feldman [?]

Table 6: **gf** values and observed lines in the 3d-4f array

The **3** items in each element are the **gf** value, the observed intensity, and the **wavenumber**.

$[K]J$	4f $[2\frac{1}{2}]_3$	$[2\frac{1}{2}]_2$	$[3\frac{1}{2}]_3$	$[3\frac{1}{2}]_4$	4f' $[3\frac{1}{2}]_3$	$[3\frac{1}{2}]_4$	$[2\frac{1}{2}]_3$	$[2\frac{1}{2}]_2$	$[4\frac{1}{2}]_5$	$[4\frac{1}{2}]_4$	$[1\frac{1}{2}]_1$	$[1\frac{1}{2}]_2$
$3d\ ^1D_2$	1.67	0.05	1.71		0.55		0.18	0.24			0	0.20
	3	2										
	6239	6246										
$3d\ ^3F_2$	0.15	0.23	1.90		2.70		0.01	0.01			0	0
			2		3							
			5727		5787							
$3d\ ^3F_3$	0.24	0.03	0	2.73	0.46	1.77	0	0.01		1.96		0
				3		2				3		
				5710		5770				5800		
$3d\ ^3F_4$	0.01		0	0.20	0.02	0.72	0.05		8.20	0.16		0.02
									10			
									5765			
$3d\ ^3D_1$		2.63						0.02			0.22	0
		15b										
		5626										
$3d\ ^3D_2$	2.06	0.36	0.90		0.91		0.06	0.41			0.09	0.20
	14		9.7		10							
	5612		5618		5678							
$3d\ ^3D_3$	0.08	0.01	0.17	3.25	0.17	2.18	0.93	0.06		0.17		0.05
	2.7			17b		15b	3b					
	5601			5608		5668	5494					
$3d\ ^1F_3$	0.20	0	0.20	0.46	0.12	1.94	0.05	0.01		4.40		0.01
	3.0					10.4	2.0			15.4		
	5390					5456	5483			5486		
$3d\ ^1P_1$		0.13						1.33			0	1.08
		b – atm						10.1				7.6
		5188						5282				5305
$3d\ ^3P_2$	0.37	0.03	0		0		3.11	0.23			0.04	0.38
	2.3						11.0	bs			lb	2b
	4608						4702	4702			4725	4725
$3d\ ^3P_1$		0.07						0.67			0.64	1.12
		0.3						4.1			5b	6b
		4608						4694			4717	4717
$3d\ ^3P_0$											0.86	
											4.1	
											4713	

Table 6: Coincidental transitions placing the 4d $^1F_3$ level 5 cm^{-1} above the **Johansson** value

Designation	gf	Ohs. wavenumber	talc.	Intensity
4p $^1D_2$ - $4d\,^1F_3$	*5.3*	*2182.680*	defining	1.5
$4d\,^1F_3$ -5p $^1D_2$	2.3	(1447.57)	Not observed	
$4d\,^1F_3$ - $5f\,[2\frac{1}{2}]_3$	0.17	2459.474	.437	0.4
$4d\,^1F_3$ - $5f\,[3\frac{1}{2}]_3$	0.17	2461.943	.947	0.4
$4d\,^1F_3$ - $5f\,[3\frac{1}{2}]_4$	0.39	2462.13	.147	0.3
$4d\,^1F_3 - 5f'\,[3\frac{1}{2}]_4$	*1.6*	*2517.23*	*.117*	*0.3*
$4d\,^1F_3 - 5f'\,[4\frac{1}{2}]_4$	*3.7*	*2535.410*	*.421*	*2.86*
$4d\,^1F_3$ -6p $^1D_2$	*0.16*	*3265.733*	*.717*	*0.3*

Table 7: Observed lines and the 4d $^1F_3$ level'

The 3 lines are specified with the expected intensities. For each proposed value of the 4d $^1F_3$ **level(J** is **Johansson's** value), the calculated wavewnumbers are followed by the observed **wavenumbers** and intensities.

$4d\,^1F_3$	$4p\,^1D_2 - 4d\,^1F_3$	1.1	$4d\,^1F_3 - 5f'\,[3\frac{1}{2}]_4$	0.3	$4d\,^1F_3 - 5f'\,[4\frac{1}{2}]_4$	0.6
83946.86	***2177.00***		***2522.91***		***254110***	
	2176.985	**5.1*b***	***2522.91***	0.1	2541.121	0.8
83947.08	2177.22		2522.69		2540.88	
	2177.205	**1.0*b***	2522.675	0.5	2540.885	***0.96***
83947.18	2177.33		2522.58		2540.77	
	2177.349	1 lb	2522.58	0.2	2540.798	***0.86***
83947.43J	***2177.57***		***2522.34***		***2540.53***	
	2177.579	***0.66***	***2522.373***	***0.36***	***2540.60***	0.16
83948.06	2178.20		2521.71		2539.90	
	2178.262	1.16	2521.743	0.1	2539.938	0.9