POSSIBLE ORIGINS FOR THE 12μ EMISSION LINES IN THE SOLAR SPECTRUM

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Braut and Noyes (1982,1983) have reported the detection of about 40 unidentified emission lines near 12μ in the solar spectrum. The strongest lines, at 811.578 cm^{-1} and 818.062 cm^{-1}, respectively, appear as broad, shallow absorption lines, less than 3% deep, with central, emission reversals projecting 5-10% above the continuum. The emission lines strengthen at the limb and over spot penumbrae but seem to be absent over spot umbrae. The full width at half-intensity of the emission lines is about 5 km/sec, but the absorption widths are more than 10 times as broad. Over spot penumbrae, the Zeeman splitting of the emission lines is striking. The lines have the appearance of a Zeeman triplet; the central component is nearly absent at the center of the disk but is very strong near the limb where the field is viewed perpendicularly to the line of sight. The splitting over spot penumbrae is about 10 times the width of the central component, and is consistent with that of a spectral line with a Landé g-factor of unity in a magnetic field of 1500 gauss. Braut and Noyes (1982, 1983) point out that the 12μ lines are a potentially powerful tool for magnetic field measurements in stars. Further observational details will be found in their referenced papers.

The great widths of the absorption features in the strongest lines probably offer a strong clue to their identifications. We consider two possible sources for the line broadening, the first being abundance broadening and the second autoionization. At first glance, it may seem surprising that such shallow absorption lines could be abundance broadened, until we realize that the wavelengths are far in the infrared, where lines formed by pure absorption have very small central depths (Mihalas 1978). For example, a line at 800 cm^{-1} formed in the sun according to the Milne-Eddington approximation will have a saturated

*This paper contains additional results and conclusions derived after the paper was presented.

**Kitt Peak is operated by AURA, Inc. under contract with the National Science Foundation.

P. B. Byrne and M. Rodonò (eds.), Activity in Red-Dwarf Stars, 327–330.

central depth of a little less than 2% of the continuum intensity. A calculation made purely for illustrative purposes shows that the observed absorption component of the solar line at 811.578 cm^{-1} can be satisfactorily represented in the LTE approximation by the following parameters: $l_o/\kappa = 10000$, $a = 0.02$, $\Delta\nu_D = 2 \times 10^8$ sec^{-1}, where l_o/κ is the ratio of line to continuous opacity at the line center, a is the ratio of damping to doppler broadening and $\Delta\nu_D$ is the doppler width in frequency units corresponding to a velocity of 2.5 km/sec. Note that the central line absorption coefficient, which is inversely proportional to the doppler width, is at least 20 times larger at 12μ than in the visible. This circumstance favors the appearance of a sharp, central emission, which, in the abundance broadening model, would be formed in the low chromosphere in the presence of a negative temperature gradient. As to the specific element or elements responsible for the 12μ lines, such abundant atoms as Fe I, Mg I and Si I should be looked at in the laboratory. It is possible that the reason the wavelengths cannot be calculated from existing tables of energy levels is because the transitions may involve configurations with outer f-electrons, which require infrared laboratory spectra for their detection.

A second possibility is that the lines may arise from transitions between doubly-excited levels, one or both of which is autoionizing. Since the lines are stronger in spot penumbrae than in the photosphere, one thinks in terms of an abundant, neutral atom in which the first excited state of the ion has a relatively low excitation potential. An obvious candidate is neutral calcium, which is known to possess a large number of doubly-excited levels converging on the first excited level 3d ^{2}D of Ca+. For example, a recent compilation (Sugar and Corliss, 1979) lists about 200 such levels, nearly all of them with J = 1 and belonging principally to the odd configurations 3dnp and 3dnf, with n-values as large as 58. Only odd levels with J = 1 may combine with the ground level of Ca I and thereby be relatively easily observed in absorption in the laboratory. Fourteen levels of the even configurations 3d4d, 3d5d and 3d6d are also listed by Sugar and Corliss as lying above the first ionization limit of Ca I. Inspection of the Sugar-Corliss table shows that a large number of transitions with $\Delta n = 0$ and ± 1 occur throughout the infrared spectrum. However, no exact coincidences in frequency could be found for the three strongest solar lines at 12.2μ. This is not surprising, considering that most of the observed levels are of odd parity with J = 1 and relatively few even levels are known.

If the transitions involve autoionizing levels, it is not obvious how the central emission reversals would be produced. One possibility is that the lines are optically thick and are formed near the photosphere-chromosphere temperature minimum, analogously to the H and K lines of Ca+. Here, a rough calculation demonstrates that there are far too few excited Ca I atoms along the line of sight through the region in which the temperature of the low chromosphere is increasing outward. Part of the problem is that, unlike profiles with Doppler cores, the pure Lorentzian absorption coefficient expected for lines arising from

https://doi.org/10.1017/S0252921100096251 Published online by Cambridge University Press

autoionizing levels is relatively small at the line center and decreases very slowly away from the center. If due to Ca I, the emission lines would have to be formed in the photosphere, which would be possible, in principle, by laser action. According to the selection rules for autoionization in LS coupling, radiationless transitions between a term in a doubly-excited configuration and a virtual term in the continuum can only occur when the parity and the L-value of the term are unchanged. This means, for example, that certain terms of a given configuration are autoionizing, while other are not, as follows:

Configuration	Terms	
	Autoionizing	Non-Autoionizing
3dnp	^{31}FP	^{31}D
3dnd	^{31}GDS	^{31}FP
3dnf	^{31}HFP	^{31}GD

Autoionizing levels are closely coupled to the continuum and therefore their populations relative to the ground state of the ion will be close to those given by the Saha-Boltzmann equation. In other words, the factor b_n, defined as the ratio of the true level population to that in thermodynamic equilibrium, will be unity or close to it. Levels that do not autoionize and are populated chiefly by radiative capture will be underpopulated as compared with LTE - their b_n-factors will be less than unity. Thus, for a transition between a lower non-autoionizing level and an upper autoionizing level, we may have a situation in which $b_L < b_U$, where b_L and b_U are the departure coefficients of the lower and upper levels, respectively. If $b_U > b_L$, the line absorption coefficient may become negative and amplification of the line intensity may occur. The condition is that $(b_U/b_L)\exp(-hc\tilde{\nu}/kT) > 1$ (Goldberg, 1966). Taking $\tilde{\nu} = 800$ cm^{-1} and $T = 4000°$ K, we find that the condition for amplification is $b_U/b_L > 1.3$, or, with $b_U = 1$, $b_L < 0.75$, a value that seems not unreasonable for Ca I levels in the 3d4d or 3d5d configurations, which lie about 0.7 eV below the 3d ionization limit. Model calculations should be performed as a test of the Ca identification and laser mechanism hypothesis.

It should also be possible to test the proposed identification by direct measurements of doubly-excited energy levels in the laboratory. As mentioned earlier, the 3dnd levels are of even parity and do not combine directly with the ground state. In recent years, however, physicists have made a major breakthrough in the study of excited atomic and molecular states through the development of two-photon, laser spectroscopy. For example, the singly-excited 4sns and 4snd levels have been observed to very high quantum numbers by this technique (Esherick, Armstrong, Dreyfus and Wynne, 1976), and it would be of considerable astrophysical importance if the measurements could be extended to the doubly-excited even levels as well.

REFERENCES

Esherick, P., Armstrong, J. A., Dreyfus, R. W., and Wynne, J. J. 1976, *Physical Review Letters*, 36, 1296.
Brault, J. and Noyes, R. W. 1982, to be submitted to *Ap. J. Letters*.
Brault, J. and Noyes, R. W. 1983, *paper presented at IAU Symposium No. 102, J. Stenflo (ed.)*.
Sugar, Jack and Corliss, Charles 1979, *Journal Phys. Chem. Ref. Data*, 8, 865.
Goldberg, L. 1966, *Astrophys. Journal*, 144, 1225.
Mihalas, D. 1978, *Stellar Atmospheres, 2nd Edition, p313, W. H. Freeman and Company, San Francisco*.

DISCUSSION

Mattig: In your sunspot spectra the shifted (σ) lines are much broader than the unshifted (ρ) one. Can you explain this?

Goldberg: My guess is that we are looking close to the limb and therefore almost horizontally. So I think you are seeing the radial gradient of the magnetic field in the penumbra, which drops off very rapidly with distance and that is why those components are so broad. The central component is not affected.

Worden: With current detector technology it is highly unlikely that these features will be observed in stars. Do you have an idea for a suitable target stars?

Goldberg: I think that Noyes and Brault are planning to look at some stars. They should stay away from red supergiants which have very broad lines. I calculated that at this wavelength the Zeeman splitting for a field of the size mentioned would be about the same as the Doppler width. So I think one should go to bright giants and Capella would be my first choice.

https://doi.org/10.1017/S0252921100096251 Published online by Cambridge University Press