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Ca I LINES IN AUTO-IONIZATION IN THE SOLAR SPECTRUM

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ABSTRACT

It is proposed that (1) the three broad, weak depressions at λλ 6362, 6344, and 6319 in the solar spectrum correspond to the transitions in a multiplet of the Ca I atom and (2) their diffuse character results from the fact that the atom is subject to auto-ionization when it is in the upper state of the transition.

In the Utrecht *Atlas* of the solar spectrum (Minnaert, Mulders, and Houtgast 1940) there may be seen two broad, weak depressions of 3–6 per cent of the continuum near λλ 6362 and 6344. Though very diffuse these features are readily noticed; they are apparently symmetrical and exhibit no marked center-limb behavior in photoelectric records made some time ago by one of the authors (W. E. M., Jr.), but they appear not to have been identified with any atomic or molecular species (St. John, Moore, Ware, Adams, and Babcock 1938; Sitterly 1964).

In a number of rather compressed but high-resolution spectrum tracings made with the McMath-Hulbert spectrometer at the Snow telescope on August 13, 1963, a third diffuse feature was noted near λ 6318. It was also noted that the character of the depression, although obscured by a strong Fe line and ten other atmospheric and unidentified features of different strengths (St. John *et al.* 1928), bears a striking resemblance to the two depressions at longer wavelengths which are so easily seen in the Utrecht *Atlas*.

An examination of the multiplet tables (Moore 1945) showed that the wavelengths of the Ca I transition $3d4p\,^3F - 3d4d\,^3G$ were close to the measured positions of the three diffuse features. Table 1 gives the data measured from the tracing shown in Figure 1 together with the wavelengths from the multiplet tables. The strengths given in the last column are the products of the measured half-widths and depths.

The record in Figure 1 was made in the fourth order of grating 91B with the McMath-Hulbert spectrometer employed in the single-pass (Mitchell and Mohler 1964). Integrated sunlight was fed to the spectrometer during the observations.

The somewhat discordant wavelengths of Table 1 may result from the lack of good laboratory observations (Sitterly 1964). The purpose of this note is to propose, nevertheless, that the three weak depressions, which are shown in Figure 1 and described in Table 1 arise from the Ca I transition $3d4p\,^3F–3d4d\,^3G$ (multiplet No. 53) and that their shallowness and breadth in all probability result from the fact that they are produced in auto-ionization.

It was noted that the calcium identification has also been suggested at the wavelengths 5735.7, 5746.8, and 5761.9 Å (St. John *et al.* 1928). These are wavelengths in the Ca I transition $3d4p\,^3F^o–3d4d\,^3F$ (multiplet No. 54), a transition also subject to auto-ionization. The region containing these lines was examined in our own tracings and in the Utrecht *Atlas*. Of the seven members of the multiplet the regions of four (λλ 5761.9, 5757.7, 5746.8, and 5735.7) contain a number of unblended features which are depressions from 0.8 per cent up to 5 per cent of the continuum but whose half-widths are less than 0.15 Å. The remaining three regions (λλ 5531.7, 5518.0, and 5507.0) have a number

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1965ApJ...141.1126M

of blended lines, also of small half-widths. These half-widths are all less than one tenth those of Table 1. Highly compressed tracings of the region of this multiplet have not yet been recorded and examined, however, so that the decision as to the presence or absence of the diffuse type features of Figure 1 in the case of the transition $3d4p\,^3F$–$3d4d\,^3F$ should be deferred.

The property of auto-ionization, known as the Auger effect in X-ray spectra and resembling predissociation in molecular spectra, is one in which not only the ordinary valence electron but also a second electron is excited. The occupation of discrete levels by two excited electrons gives rise to energy levels which lie above the ionization energy of the atom (Bohr and Wentzel 1923; White 1934; Herzberg 1937; Condon and Shortley 1957; Kuhn 1962). In jumping upward to a discrete level of negative energy, i.e., to a level lying in the ordinary first ionization continuum, an electron may acquire a proba-

TABLE 1

LINES OF THE Ca I TRANSITION $3d4p\,^3F^o$–$3d4d\,^3G$

Wavelength (Å)		Δ (Snow-RMT)	Half-Width (Å)	Depth (Per Cent)	Strength (mÅ)
Multiplet Tables	Snow Telescope				
6361 79	6361 94	+0 15	2 7	2 4	65
6343 29	6343 71	+ 42	2 6	3 0	78
6318 11	6318 61	+0 50	2 4	3 3	79

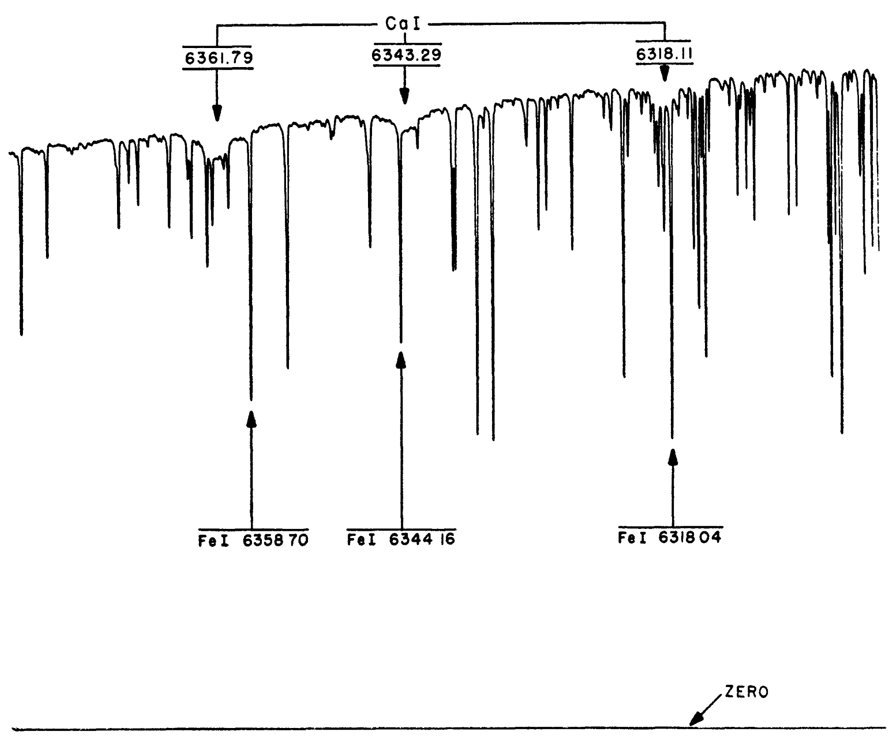

FIG. 1 —Lines of the Ca I transition $3d4p\,^3F^0$–$3d4d\,^3G$ in the solar spectrum. Its upper levels are subject to auto-ionization.

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1965ApJ...141.1126M

bility of becoming a free electron by means of a radiationless quantum jump. The effectively shortened half-life of the electron in the upper level evidences itself in the production of a broadened absorption line as in the case under discussion. Conversely, in the downward transition an effectively shortened half-life of the electron in the upper level evidences itself in the production of a broadened emission line.

Laboratory studies, particularly those by Allen (1932*a*, *b*) of the Cu I spectrum, have dealt with the process of auto-ionization in the emission spectrum, the explanation being due to Shenstone (comment following Allen's papers). White (1934, p. 396) illustrates the phenomenon for the case of a one-electron jump in the arc spectrum of copper and, in addition, describes (pp. 397, 398) the effect in transitions involving two-electron jumps in the arc spectra of calcium, strontium, and barium. For Ca I in particular studies of (1) the absorption continuum from 2028 to 1950 Å have been reported by Jutsum (1954), (2) the two series of auto-ionization lines between 1950 and 1600 Å by Kaiser (1960), and (3) both the auto-ionization lines and the absorption continua from 2100 to 1080 Å by Ditchburn and Hudson (1960).

On the other hand, theoretical probabilities of auto-ionization have been calculated, for the case of He I, by Bransden and Dalgarno (1953). In the astrophysical literature, however, transitions with this property and their appearance in absorption spectra seem to have merited scant practical attention (Mitchell 1958, pp. 133 ff.), probably because of the weak and diffuse character of the lines and the difficulty of identification.

Condon and Shortley (1957, p. 370) point out that the spectroscopic effects on lines whose initial levels are subject to the phenomenon are (1) a broadening, and (2) an intensity varying with electron pressure. Now in the case of type-G and later stars the electron pressure plays an important role in the continuous opacity of the stellar atmosphere owing to the influence of the negative hydrogen ion. In these atmospheres the dependence on the electron pressure of lines not formed in auto-ionization may be summed up as follows: for a fractional change, Δ, in the electron pressure, the corresponding fractional change in the ratio of line to continuous absorption is approximately:

	Neutral Lines	Ion Lines
Element predominately neutral .	$-\Delta$	-2Δ
Element predominately ionized . . .	0	$-\Delta$
Element 50 per cent ionized	0	-2Δ

For lines produced in auto-ionization, however, the fractional change should be approximately zero no matter what the extent of ionization of the atom.

Dielectronic recombination is said to occur when an electron descends from a level subject to auto-ionization to a level not subject to auto-ionization (Bates and Dalgarno 1962). Its astrophysical importance has recently been pointed out by (1) Burgess (1964) in reconciling coronal temperatures obtained from ionization balance calculations and from observed Doppler line-broadening, and (2) Goldberg (1964*a*) in proposing an explanation for the emission reversals in the Fraunhofer H- and K-lines. Additional interesting astrophysical roles for both phenomena—dielectronic recombination and auto-ionization—are also considered by Goldberg (1964*b*).

The natural breadths of lines whose upper levels are subject to auto-ionization would in general appear to dwarf sources of broadening such as magnetic splitting and Doppler broadening associated with large-scale motions. The dominance of the natural line broadening has the interesting consequence that these lines ought to exhibit more of a weak-line character and freedom from curve-of-growth effects than any other lines in the spectrum—even than those of much smaller equivalent width.

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1965ApJ...141.1126M

In *Atomic Energy Levels* (Moore 1949, 1952, 1958) 38 different atoms through actinium exhibit negative energy levels in a total of 52 stages of ionization. These are listed in Table 2. The energy levels in these species which are to some extent subject to auto-ionization (and hence capable of giving rise to diffuse lines) are not in general identified as such. In order to determine whether a spectrum feature is likely to be broadened by this phenomenon, one must (1) consult the references to the spectrum analyses found in *Atomic Energy Levels* or (2) examine the term scheme containing the levels in the transition in question. Negative terms cannot go over by radiationless transitions into the continuum above any arbitrary term sequence; consequently, the selection rules for radiationless transitions must be applied (Herzberg 1937, p. 173).

In conclusion, the record of Figure 1 illustrates the usefulness of spectra which combine the highest possible resolving power with low dispersion recording. Shenstone (1940) ascribes the once long-standing difficulty in the analysis of the arc spectrum of silver to the fact that "instruments of too great dispersion were used for the detection of very diffuse lines." The need for coupling the highest possible resolving power with low dispersion in the case of the absorption spectra of the Sun and stars is, of course, to delineate as clearly as possible the slowly varying background from all overlying features.

TABLE 2

ELEMENTS WITH KNOWN NEGATIVE ENERGY LEVELS

He I Be I B I C I, II, III N III, IV	O II, III, IV, V F II, IV, V, VI Na IV, VI	Mg I, V Al I Si II P II, III Ar I	K I Ca I V I Cr I Mn I	Cu I Zn I Ga I Ge II Kr I	Rb I Sr I Mo I Ag I Cd I	In I Sn I, II Sb I Xe I Cs I	Re I Au I Tl I Pb V Bi I, VI

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