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WAVELENGTHS OF FORBIDDEN TRANSITIONS ARISING FROM LEVELS WITHIN THE Fe^{+19} $2s^22p^3$ GROUND CONFIGURATION

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ABSTRACT

In this paper we report the identification of all remaining unidentified forbidden lines arising from transitions within levels of the Fe^{+19} ground configuration. These lines were identified using data from the *SOHO*/SUMER spectrograph and *Skylab*. Adjusted wavelength values are also given for some previously observed lines. Forbidden lines that are the result of transitions within levels of the ground configuration of a highly ionized astrophysically abundant element generally have longer wavelengths than resonance lines emitted by the same ion. Many of these forbidden lines are fairly prominent in low-density plasmas and traditionally have been used in determining properties of high-temperature astrophysical plasmas. The identified Fe^{+19} forbidden lines span the 300–2665 Å wavelength range. Since spontaneous decay rates of forbidden transitions arising from the same upper level are known quite accurately, these lines can be used for calibrating spectrometers over wide wavelength ranges.

Subject headings: Sun: corona — Sun: UV radiation — techniques: spectroscopic

1. INTRODUCTION

Under the low-density conditions that exist in solar coronal plasmas Fe^{+17}–Fe^{+23} ions reach their maximum fractional abundance at temperatures of 5×10^6–2×10^7 K. It is, therefore, not surprising that when the extreme-ultraviolet (EUV) spectrum emitted by solar flares was first recorded (Kastner, Neupert, & Swartz 1974) interest in deciphering the then unknown energy structure of Fe^{+17}–Fe^{+23} ions arose in the atomic physics community. In the mid-1970s powerful lasers, which had become available only a short time earlier, were the most efficient laboratory sources for generating the plasma conditions needed to ionize Fe atoms to conditions prevalent in solar flares. Utilizing emission from high-temperature laser-produced plasmas, Doschek et al. (1974) and Feldman et al. (1975) recorded highly ionized spectra from many elements belonging to the fourth row of the periodic table. Based on these observations they identified lines emitted by Ti, V, Cr, Mg, Fe, Co, and Ni ions that belong to the F I–, O I–, N I, and C I isoelectronic sequences.

In their studies along the N I isoelectronic sequence, to which Fe^{+19} belongs, Doschek et al. (1974) and Feldman et al. (1975) identified a number of lines that originate from allowed (E1) transitions between the ground ($2s^22p^3$) and first excited ($2s2p^4$) configurations. In the following years a number of additional lines belonging to transitions within the same configurations were identified by Lawson & Peacock (1980) and by Peacock, Stamp, & Silver (1984). The wavelengths of these allowed transitions appear in the EUV part of the spectrum between 80 and 140 Å. The laser-produced plasmas, which emitted the spectral lines that Doschek et al. (1974) and Feldman et al. (1975) analyzed, had an electron density of $n_e \sim 10^{19}$ cm^{-3}. In plasmas with such high electron densities collision and not radiation is the primary depopulation process of excited transitions having long spontaneous decay rates. Thus, it is seldom that lines from "forbidden" (M1) transitions, which have fairly long spontaneous decay rates, are sufficiently bright to be observed in spectra emitted by laser-produced plasmas.

The electron densities in solar flare plasmas are significantly lower than those in laser-produced plasmas. Instead of the $n_e \sim 10^{19}$ cm^{-3} densities common in laser-produced plasmas, electron density conditions in solar flare plasmas are at least 6 orders of magnitude lower ($n_e \leq 10^{13}$ cm^{-3}). As a result, flare plasmas, which produce bright resonance lines, also emit fairly intense lines from forbidden transitions. In general, the brightest forbidden lines in the spectrum are expected to arise from transitions within levels of the ground configuration. Cognizant of this, Feldman et al. (1975) used energy levels derived from resonance transitions in highly ionized Fe ions to predict the wavelengths of some of the brightest forbidden transitions in Fe and Ni ions that were expected to be observed in flare spectra. Indeed, within a short time some of these lines were identified in flare spectra recorded by instruments aboard *Skylab* (e.g., Doschek et al. 1975). Doschek & Feldman (1976) also suggested that, since the electron density and temperature conditions in tokamak and in flare plasmas are similar, forbidden lines from transitions between ground configurations of highly ionized elements should also be observed in tokamak plasmas. In particular, they suggested that, since the walls of tokamak machines are made of stainless steel, forbidden lines emitted by highly ionized Cr, Fe, and Ni should be observed.

In the next section we discuss previous identifications of lines from transitions within the Fe^{+19} ground configuration. In § 3 we present new line identifications made with data from *Skylab* and the *Solar and Heliospheric Observatory*'s Solar Ultraviolet Measurements of Emitted Radiation (*SOHO*/SUMER). § 4 concerns the use of Fe^{+19} forbidden lines for relative intensity calibration of lines measured in the 300–2665 Å wavelength range.

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2. PREVIOUSLY IDENTIFIED LINES

The ground configuration $2s^22p^3$ in Fe^{+19} consists of five levels. The levels in increasing energy are $^4S_{3/2}$, $^2D_{3/2}$, $^2D_{5/2}$, $^2P_{1/2}$, and $^2P_{3/2}$. These levels produce nine different M1 transitions whose wavelengths occur between approximately 300 and 2700 Å. Note that the ground configuration of Fe^{+18} and of Fe^{+20} produce only five forbidden transitions each and the ground configurations of Fe^{+17} and Fe^{+21} produce only one forbidden transition.

A summary of the previously identified lines from transitions within the $2s^22p^3$ configuration in Fe^{+19} is given in Table 1, column (2). The longest of these transitions, the $^2D_{5/2}$–$^2D_{3/2}$, was detected in spectra emitted by tokamak plasmas at a wavelength of 2665.1 ± 0.3 Å (in air; Suckewer & Hinnov 1978, 1979). Because of its very long wavelengths, this line establishes to a high degree of accuracy the splitting between the two ^2D levels (37510.9 ± 4 cm^{-1}). Using solar flare spectra recorded by the Naval Research Laboratory (NRL) spectroheliograph on *Skylab*, Widing (1978) identified the 541.35 ± 0.3 Å line as the $^2P_{3/2}$–$^2D_{3/2}$ forbidden transition. Later, the same line was also observed in tokamak plasmas (Finkenthal et al. 1984). Sandlin et al. (1976) measured a flare line at 309.26 Å. This line was later identified by Lawson, Peacock, & Stamp (1981) as the $^2P_{3/2}$–$^4S_{3/2}$ forbidden transition. Lawson et al. (1981) also proposed that the 567.76 Å line, previously measured by Widing (1978) in a flare spectrum, belongs to the $^2D_{5/2}$–$^4S_{3/2}$ transition. E. Hinnov (1986, private communication to Kaufman & Sugar) used tokamak plasmas to identify the $^2P_{3/2}$–$^2D_{3/2}$ transition at 679.3 Å.

Edlén in his 1984 paper studied the regularities of energy levels within the ground configuration ($2s^22p^3$) and first two excited configurations ($2s2p^4$, $2p^5$) for elements in the N I isoelectronic sequence. His study encompassed all elements with atomic numbers of $10 \leq z \leq 36$, i.e., Na–Kr. Edlén (1984) compared experimentally derived wavelengths and wavelengths from theoretical calculations by Cheng, Kim, & Desclaux (1979). In utilizing the differences between experimental and theoretical calculations, he derived new energy values intended to reduce the accidental errors in the experimental values. The wavelengths of the forbidden transitions that resulted from Edlén's newly derived ground configuration levels are given in Table 1, column (3).

3. NEW IDENTIFICATIONS

With the launch of SUMER (Wilhelm et al. 1995), a previously scarcely explored part of the solar spectrum ($500 < \lambda < 1100$ Å) became accessible to spectroscopic studies. However, the mode of the SUMER operation is such that at any time it records a spectrum over a spectral range of not more than ≈43 Å. Because of this, only a short section of the SUMER wavelength range is recorded during transient events. A case in point is the high-temperature spectrum that was reported by Feldman et al. (1998). During the ≈5 hr that it takes SUMER to record a 300″ wide solar spectrum over its full wavelength range, emission from the short-duration flare appeared only on a small number of frames. Although the particular frames included forbidden lines emitted by Fe^{+16}, Fe^{+17}, and Fe^{+18}, they did not include lines from Fe^{+19} that appear in a different part of the spectrum.

During a 1996 July 10 observing campaign a flare occurred in a solar region where SUMER happened to be pointed. Fortunately, during the same time the grating of the SUMER spectrometer was in the proper orientation to record in second order the $^2D_{3/2}$–$^4S_{3/2}$ forbidden transition of Fe^{+19}. By comparing the position of this line with the positions of nearby known neutral sulfur lines, a wavelength of 721.56 ± 0.01 Å was derived for the Fe^{+19} line. A composite SUMER spectrum in the appropriate wavelength recorded during the flare and during a nonflaring period is shown in Figure 1.

Motivated by the SUMER finding we reexamined published and unpublished results of flare spectra, which were recorded by the NRL SO82a spectroheliograph on *Skylab*, and found the following. By adding the energy of the newly measured SUMER line and the energy of the tokamak 2665.1 Å (in air) line, we establish the energy of the $^2D_{5/2}$–$^4S_{3/2}$ transition as 176,110 cm^{-1}, corresponding to a wavelength of 567.82 Å. Dere (1978) lists a line at 567.85 Å observed by *Skylab* in a flare that occurred on 1973 December 17. This line is visible in the flare spectroheliograms that are published in the atlas of *Skylab* spectra by Feldman, Purcell, & Dohne (1987) and is clearly associated with the hot flare plasma. We identify the 567.85 Å line as the $^2D_{5/2}$–$^4S_{3/2}$ forbidden transition.

Edlén (1984) predicted the wavelength of the $^2P_{1/2}$–$^4S_{3/2}$ forbidden transition to be 384.29 Å. This wavelength is quite close to the second-order wavelength of the very intense 192.04 Å ($2s$ $^2S_{1/2}$–$2p$ $^2P_{3/2}$) resonance transition of Fe^{+23}. Thus, in large flares the Fe^{+19} and second-order Fe^{+23} are blended together on the *Skylab* spectroheliograms. Upon reexamining the *Skylab* spectral records we found a hot compact flare on 1973 August 9 in which blend-

TABLE 1

Wavelengths of Forbidden Transitions within the $2s^22p^3$ Ground Configuration of Fe^{+19}

Transition (1)	Previously Measured Values (Å) (2)	Edlén's Fitted Values (Å) (3)	Adopted Values (Å) (4)	Spontaneous Decay Rates (s^{-1}) (5)
$^2P_{3/2}$–$^4S_{3/2}$	309.26	309.32	309.29 ± 0.02	2.73×10^4
$^2P_{3/2}$–$^2D_{3/2}$	541.35 ± 0.03	541.41	541.35 ± 0.02	4.49×10^4
$^2P_{3/2}$–$^2D_{5/2}$	679.3 ± 0.3	679.4	[679.29][a]	1.28×10^4
$^2P_{3/2}$–$^2P_{1/2}$	...	1585.6	1586.3 ± 0.3	1.60×10^3
$^2P_{1/2}$–$^4S_{3/2}$	...	384.29	384.22 ± 0.02	3.15×10^4
$^2P_{1/2}$–$^2D_{3/2}$	...	822.1	821.74 ± 0.05	6.17×10^3
$^2D_{5/2}$–$^4S_{3/2}$	567.76	567.86	567.84 ± 0.02	1.24×10^3
$^2D_{5/2}$–$^2D_{3/2}$	2665.1 ± 0.3 (in air)	2665.0	2665.1 ± 0.3	4.17×10^2
$^2D_{3/2}$–$^4S_{3/2}$	...	721.6	721.55 ± 0.02	1.56×10^4

[a] Derived from energy level calculations.

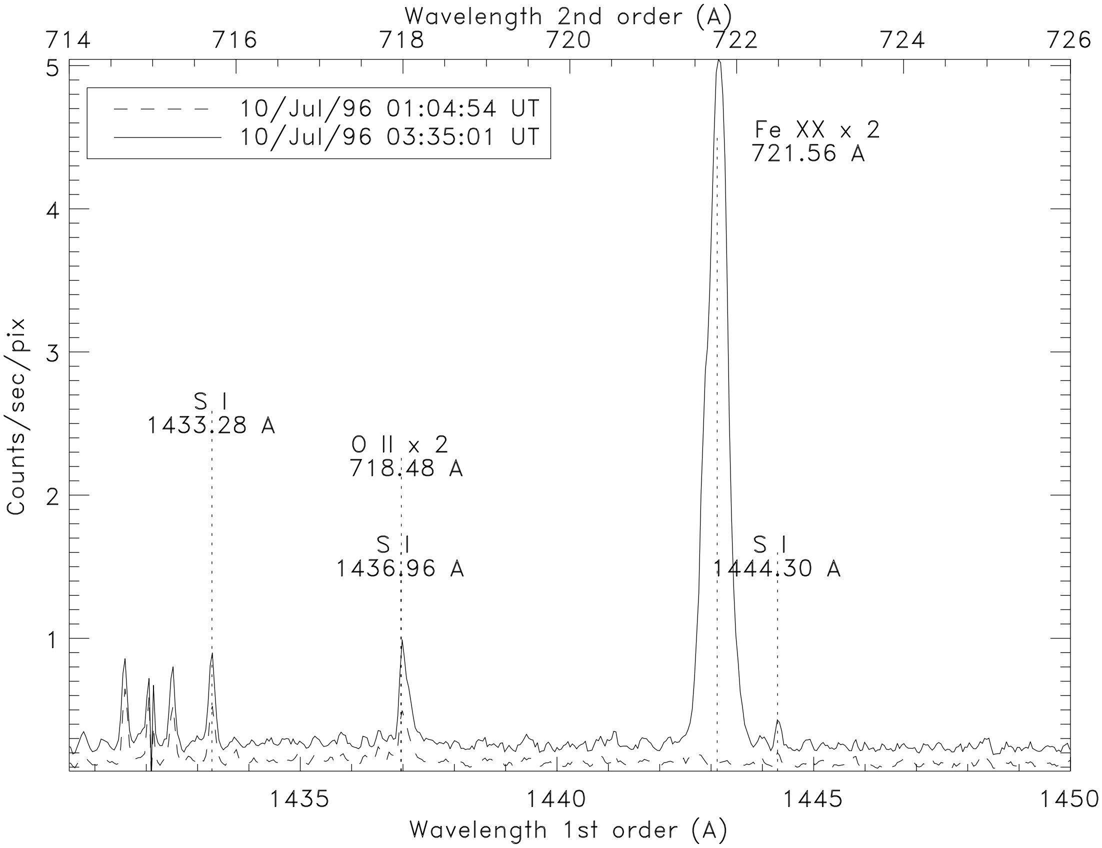

FIG. 1.—SUMER spectra from the quiet sun (*dashed line*) and flare (*solid line*). The S^0 lines at 1433.28 and 1444.30 Å were used to calibrate the wavelength of the Fe^{+19} flare line.

ing was insignificant. In the spectrum from this event we discovered next to the second-order Fe^{+23} line an additional flare line. The newly identified flare line is at 384.22 Å, 0.07 Å shorter than the wavelength predicted by Edlén.

By adding the energies of already measured 541.35 and 721.55 Å lines, we predicted the wavelength of the $^2P_{3/2}$–$^4S_{3/2}$ transition to be at 309.30 Å, some 0.02 Å shorter than the wavelength predicted by Edlén (1984). Upon inspecting the *Skylab* plates for 1973 December 17 we found an unidentified flare line at 309.29 Å that we associate with the $^2P_{3/2}$–$^4S_{3/2}$ forbidden transition. Based on the measured wavelengths we calculated the wavelengths of the two remaining unidentified forbidden transitions $^2P_{1/2}$–$^2D_{3/2}$ and $^2P_{3/2}$–$^2P_{1/2}$ at 821.83 and 1586.07 Å, respectively. The new wavelength predictions differ by 0.3 and 0.5 Å from those of Edlén (1984).

TABLE 2

ENERGY LEVELS WITHIN THE $2s^22p^3$ GROUND CONFIGURATION IN Fe^{+19}

Level	Energy (cm^{-1})
$^4S_{3/2}$	0
$^2D_{3/2}$	138589 ± 2
$^2D_{5/2}$	176098 ± 10
$^2P_{1/2}$	260275 ± 7
$^2P_{3/2}$	323317 ± 10

On 1999 May 9 while SUMER was taking a full reference spectra of an active region above the limb a fairly long duration flare occurred in the same location. Upon inspecting the spectra from this flare we successfully identified two of the remaining unidentified lines at 821.74 ± 0.05 and 1586.3 ± 0.3 Å. The 1586.3 Å line position was difficult to measure because the Fe^{+19} line was blended with a Cr^{+17} line observed in second order at 793.12 Å (Hinnov et al. 1982). Because Fe^{+19} and Cr^{+17} have significantly different formation temperatures (4×10^6 and 8×10^6, respectively; Mazzotta et al. 1998), they displayed different spatial distributions. By comparing the spatial locations of the 1586.3 Å line emission with that of unblended lines produced in the same temperature ranges as Fe^{+19} and Cr^{+17}, we were able to determine that the Fe^{+19} line did contribute to the emission at 1586.3 Å. However, we could not separate it from the Cr^{+17} line to measure a more accurate line position. A third line that was measured in tokamak data at 679.3 Å was too faint to be observed in the SUMER spectra. We also used the 1999 May 9 flare spectra to remeasure the $^2D_{5/2}$–$^4S_{3/2}$ line at 567.83 Å. We average this value with that measured in the *Skylab* observations mentioned above.

Table 1 column (4) lists the values we have adapted for the forbidden transitions within the $2s^22p^3$ ground configuration of Fe^{+19}. The 309.29, 567.84, 721.55, 821.74, and 1586.3 Å values were determined using *SOHO*/SUMER and *Skylab* observations as described above. The 541.35 and 2665.1 Å values are based on previous measurements (see § 2). The 679.29 Å value was derived from energy level calculations using the new line identifications. This should be an improvement on the previous tokamak measurement of 679.3 ± 0.3 Å.

The energy levels of the Fe^{+19} $2s^22p^3$ ground configuration derived from the measured forbidden lines in Table 1 column (4) are given in Table 2.

4. Fe^{+19} FORBIDDEN LINES AS A MEANS OF RELATIVE INTENSITY CALIBRATION IN THE 300–2665 Å RANGE

A common problem encountered in space research is the need to determine relative internal efficiencies of spectrometers operating over wide wavelength ranges. One of the methods traditionally used in such tasks relies on the presence of emission lines with widely varying wavelengths arising from a common upper level. In using such lines with well-known spontaneous decay rates, branching ratios between appropriate sets of lines can be determined. Unfortunately, finding sets of lines fulfilling the above requirement is difficult because most lines of comparable intensities arising from a common upper level appear in close wavelength proximity to each other. The forbidden lines arising from the Fe^{+19} ground configuration are unique in this respect. Transitions arising from the highest level in the ground configuration, the $^2P_{3/2}$, produce lines that could enable the cross calibration of the spectral ranges near 309, 541, 679, and 1586 Å. Transitions arising from the $^2P_{1/2}$ level could allow calibration between the ranges near 384 and 821 Å, and transitions arising from the $^2D_{5/2}$ can do the same for wavelengths near 567 and 2665 Å. Spontaneous decay rates for the forbidden transitions arising from the Fe^{+19} ground configuration were published by Bhatia & Mason (1980) and by Kaufman & Sugar (1986). The agreement between the two sets of calculations was better than 15%. Recently A. K. Bhatia (1999, private communication) recalculated the spontaneous decay rates using experimental energy level values. His new calculated values, which are almost always somewhere in between values from the previous two calculations, are given in the last column of Table 1.

5. CONCLUSIONS

With the measurement of the Fe^{+19} lines at 721.55, 821.74, and 1586.3 Å by *SOHO*/SUMER and 309.29, 384.22, and 567.84 Å by *Skylab* all lines corresponding to forbidden transitions in the $2s^22p^3$ ground configuration of Fe^{+19} have been identified. A remaining line at 679.3 Å has been identified in tokamak data but has yet to be observed in a solar spectrum. These lines will be useful in the calibration of space-borne spectrometers spanning the 300–2665 Å wavelength range.

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