

# A Note on the Solar Iron Abundance

Hong Sik Yun

Department of Earth Science

College of Education, Seoul National University

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## Abstract

An attempt has been made to re-evaluate the photospheric iron abundance by comparing computed theoretical line profiles with observations. Our resulting abundance is found to be in good agreement with that of Garz and Kock (1969), when the logarithmic abundance of iron is taken to be 7.5.

## I. Introduction

The problem of determining the chemical abundance in the solar atmosphere has attracted attentions of many astronomers for over forty years. One of the main reasons for our interest in the chemical composition is the fact that the chemical composition provides important input data to construct reliable models of the interiors and the atmospheres, which are needed to study theories of nucleogenesis and the formation of the solar and stellar systems and their subsequent evolution.

Our Sun is particularly useful because the solar spectrum can be observed over a broad range of wavelength with high spectral resolution. In addition, due to its proximity to the Earth, one can investigate the Sun with a greater variety of techniques than is possible with other stars.

## II. Earlier photospheric iron abundances

The solar iron abundance has been intensively investigated since Pottasch (1963) published that his abundance determined from coronal lines turned out to be larger than the photospheric value by a factor of approximately 10. Some workers argued that the solar photospheric abundance was spurious. Evidence for such argument was first revealed by Swings (1965), who, for the first time, identified the presence of the forbidden [Fe II] lines in the photospheric spectrum. Later, Swings and his associates (Swings 1966, Grevesse and Swings 1969, Nussbaumer and Swings 1970) showed that the photospheric iron abundance had to be raised by an order of magnitude in order to account for the presence of the forbidden iron lines in the photosphere.

Once the new [Fe II] results became available, the old measurements of the oscillator strength started to be re-examined by a number of workers such as Huber and Tcbey (1968), Whaling *et al.* (1969), Garz and Kock (1969), Wolnik *et al.* (1970) and others. As the result, it has been found that Corliss and his co-workers (1962) over-estimated their oscillator strength of certain high excitation lines of FeI by an order of magnitude.

With their new measured values of the oscillator strength of Fe I and FeII, Garz and Kock determined the photospheric iron abundance, obtaining the logarithmic abundance, to be 7.6 (whose scale is based on the logarithmic hydrogen abundance  $\log N(H)=12$ ), which is a substantial increase over the earlier value 6.54 by Goldberg *et al.* (1964). Noting that the new photospheric abundance then agreed with the Pottasch's value, it appeared that the problem on the discrepancy of the solar iron abundance existing between the photosphere and the corona had been solved.

However, later Ross (1970) claimed that the photospheric iron abundance of Garz and Kock determined from their curve-of-growth analysis could not account for theoretical line profiles such as Fe I 5434.5 and Fe I 5568.6. According to his investigation, the correct abundance should not be larger than  $\log N(Fe) = 7.2$ , which differs from Garz and Kock's value by a factor of roughly 2.5.

Cowley (1970) also made a similar investigation based on the strength of the wings of Fe I lines. He compared measured strength of the wings of neutral iron lines from his photoelectric tracings of the sun with theoretical values computed with the use of the oscillator strength of Garz and Kock along

with his damping constant determined empirically. He obtained the logarithmic abundance 7.0, which is smaller than Garz and Kock's value by a factor of 4, although it is still a considerable increase over his earlier value, 6.65.

### III. Method of calculations and results

In order to resolve the apparently conflicting problem on the solar iron abundance, an attempt has been made to compute a theoretical line profile of FeI 5435.5 for comparison profile with observations made by Stellmacher and Wiehr (1970).

The theoretical line profile can be obtained by calculating the specific line intensity at different wavelengths from the center of the line. The specific intensity  $I'_\lambda(\mu)$  in a line at wavelength  $\lambda$  is given by

$$I'_\lambda(u) = \int_0^\infty S'_\lambda e^{-\tau'_\lambda/\mu} d\tau'_\lambda/\mu, \quad (1)$$

where  $S'_\lambda$  is the line source function at wavelength  $\lambda$  and  $\mu$  is  $\cos\theta$ ,  $\theta$  being the heliocentric angle. The line optical depth  $\tau'_\lambda$  at wavelength  $\lambda$  is defined by

$$d\tau'_\lambda = (\kappa'_\lambda + \kappa^\epsilon_\lambda) \rho dz$$

where  $\kappa'_\lambda$  is the mass absorption coefficient in the line at  $\lambda$  and  $\kappa^\epsilon_\lambda$  is the mass absorption coefficient in its neighboring continuum.  $\rho$  is the mass density and  $z$  is the distance along the normal to the surface measured inwards.

For simplification it is customary to assume the local thermodynamic equilibrium (LTE) prevails in the photospheric layers, even though there are some fluctuations in temperature and turbulence as evidenced in the photospheric granulation. The LTE approximation turns out to be good in the photosphere. Under the LTE condition the velocity distribution of particles is Maxwellian and the distribution of the atoms in their

different excited levels and ionization stages is determined by the Boltzmann and Saha equations. Consequently, all distributions are represented by a unique temperature,  $T$ . Hence the line and continuum source functions at each depth in the photosphere can be replaced by the Planck function,  $B_\lambda(T)$  corresponding to the local electron temperature. Accordingly, Equation (1) becomes

$$I'_\lambda(\mu) = \int_0^\infty B'_\lambda[T(\tau'_\lambda)] e^{-\tau'_\lambda/\mu} d\tau'_\lambda/\mu \quad (2)$$

with the optical depth in the line at  $\lambda$

$$\tau'_\lambda = \int_0^z (\kappa'_\lambda + \kappa^c_\lambda) \rho dz.$$

In computing the continuous mass absorption coefficient,  $\kappa^c_\lambda$ , two processes, bound-free and free-free, are considered and the contributions due to neutral hydrogen, the negative ion of hydrogen, and neutral and singly ionized helium are taken into account. The expressions for the individual continuous absorption coefficient of these species are given by Mihalas (1967).

The line absorption coefficient per gram of stellar material,  $\kappa'_\lambda$  at  $\lambda$ , is given by

$$\kappa'_\lambda = \frac{\sqrt{\pi} e^2}{m_e c^2} N^* f \frac{\lambda_0}{\Delta\lambda_D} H(a, v) \quad (3)$$

with

$$a = \frac{\Gamma\lambda_0}{4\pi\sqrt{\left(\frac{2kT}{M}\right)^2 + \xi_t^2}}, \quad v = \frac{\Delta\lambda}{\Delta\lambda_D}, \quad \Delta\lambda = \lambda - \lambda_0,$$

$$\Delta\lambda_D = \frac{\lambda_0}{c} \sqrt{\left(\frac{2kT}{M}\right)^2 + \xi_t^2}, \quad \Gamma = \Gamma_{rad} + \Gamma_{coll}.$$

In Equation (3)  $m_e$  is the mass of an electron,  $M$ , the atomic mass of the radiating atom,  $k$ , the Boltzmann constant,  $\xi_t$ , the turbulent velocity,  $\lambda_0$ , the wavelength of the line center,  $f$ , the absorption oscillator strength,  $\Gamma_{rad}$  and  $\Gamma_{coll}$ , the radiation and collisional damping constants and  $N^*$  is the number of atoms per gram of stellar material populated in the lower level of the line.  $N^*$  can be calculated using Saha and

Boltzmann relations. The function  $H(a, v)$  in Equation (3) is the well known Voigt function, which describes the combined Doppler, radiative and collisional broadenings,

$$H(a, v) = \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2}}{a^2 + (v-y)^2} dy.$$

The Voigt function has been studied and it has been tabulated (e.g., Aller (1963)).

To obtain the total damping constant  $\Gamma$ , the radiative and collisional damping constants have to be computed. The radiative damping broadening is the result of the quantum mechanical uncertainty in the energy levels involved with transitions. The actual value of the radiative damping constant is considerably small as compared with that of the collisional damping constant.

For the collisional damping, the collision of the radiating atom with neutral hydrogen and neutral helium atoms are taken into account. The collisional damping constant due to the collision by neutral hydrogen atoms is given by

$$\log \delta_H = 6.313 + 0.3 \log(0.992 + \frac{1}{M}) +$$

$0.4 \log \langle R^2 \rangle - 0.7 \log T + \log P(H)$  and the value  $\Gamma$  is taken to be  $1.06 \delta_H$  in accordance with Aller (1963). The quantity  $\langle R^2 \rangle$  is the mean square radius of the radial wave function of the upper state of the radiating atom measured in units of the radius of the first Bohr orbit and  $P(H)$  is the pressure of neutral hydrogen atoms.

For the calculation of the line profile of Fe I 5435.5 (having a  $^5F - ^5D^o$  transition and energies of 1.01 eV and 3.28 eV from the ground state), a solar model has been selected which had been constructed empirically by Yun (1970), making a successive iteration for the temperature correction until the discrepancy between the observed and computed

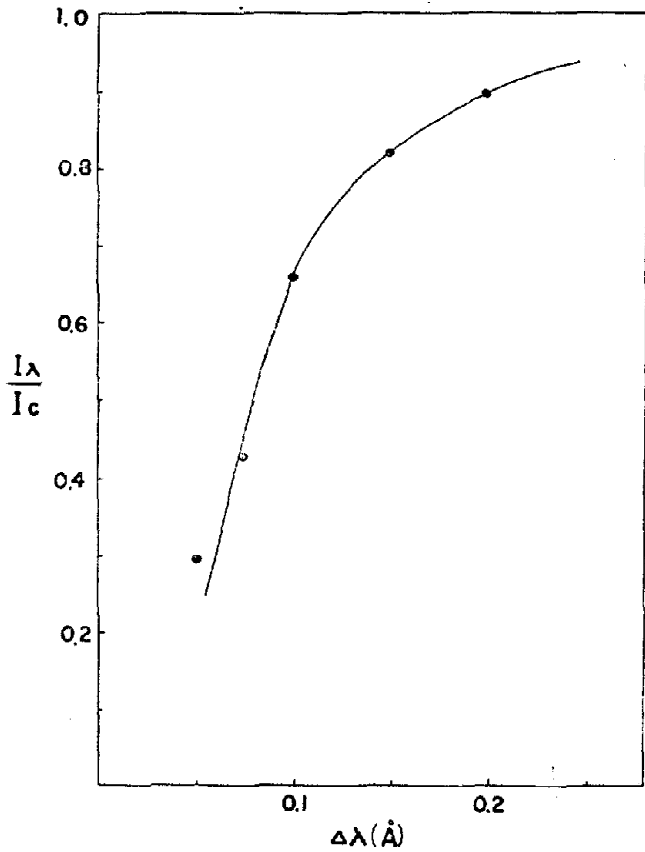


Fig. 1. The observed and computed line profile of Fe I 5435.5. The solid line represents the computed profile when the logarithmic iron abundance is taken to be 7.5 and the filled circles are the observations made by Stellmacher and Wiehr (1970).  $I_\lambda$  is the line intensity and  $I_c$  refers to the adjacent photospheric continuum intensity.  $\Delta\lambda$  is the distance from the line center in Å.

values of the emergent continuum intensity falls within one percent. The resulting solar model atmosphere is summarized in Table 1, where  $T$  is temperature,  $P$ , the gas pressure,  $P_e$ , electron pressure, and  $\tau_0$  and  $\kappa_0$  are continuous optical depth and the continuous mass absorption coefficient at a wavelength 5000Å, respectively. In the present calculation the collisional damping constant computed from Equation (4) has been multiplied by a factor of 6 to correct the hydrogenic approximation made for the calculation of the quantity  $\langle R^2 \rangle$  (which takes a value of 8.7 in the present case) in accordance with Cowley

Table 1. The computed solar photosphere

$\log \tau_0$	$T$	$\log P$	$\log P_e$	$\log \rho$	$\log \kappa_0$
-3.0	4665	3.663	-0.552	-7.787	-1.990
-2.8	4656	3.778	-0.458	-7.671	-1.893
-2.6	4655	3.890	-0.365	-7.559	-1.800
-2.4	4654	4.001	-0.274	-7.448	-1.708
-2.2	4664	4.112	-0.180	-7.338	-1.618
-2.0	4695	4.222	-0.459	-7.230	-1.526
-1.8	4764	4.332	0.041	-7.127	-1.436
-1.6	4850	4.442	0.170	-7.025	-1.342
-1.4	4954	4.551	0.301	-6.925	-1.250
-1.2	5074	4.659	0.439	-6.827	-1.152
-1.0	5129	4.767	0.553	-6.724	-1.060
-0.8	5304	4.873	0.722	-6.633	-0.951
-0.6	5509	4.973	0.923	-6.549	-0.815
-0.4	5764	5.063	1.173	-6.479	-0.639
-0.2	6084	5.138	1.484	-6.428	-0.423
0.0	6479	5.196	1.850	-6.397	-0.158
0.2	6934	5.239	2.236	-6.383	0.124
0.4	7426	5.272	2.607	-6.381	0.401
0.6	7881	5.300	2.914	-6.380	0.637
0.8	8261	5.324	3.149	-6.377	0.825
1.0	8550	5.349	3.317	-6.368	0.965

(1969). The  $f$  value of Fe I 5435.5 has been taken from Garz and Kock (1969), adopting  $\log gf = -1.87$ , and the turbulent velocity in the photosphere has been assumed to be 1 km/sec throughout the photosphere.

By varying the iron abundance numerous theoretical profiles of Fe I 5435.5 have been calculated to select a profile which represents the observation best. The resulting computed profile is shown in Figure 1, where the filled circles are the observed values of Stellmacher and Wiehr (1970).

#### IV. Conclusions

As seen from the figure, the computed profile fits well with the observations, when the logarithmic abundance is taken to be 7.5. Although there exists some uncertainty in the calculation of the line profile arising from the uncertainty in-

volved with the damping constant and the oscillator strength, it appears that the resulting photospheric abundance favors Garz and Koch's value, which is more consistent with abundance determined from coronal lines.

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