

## **Singly Ionized Iridium Spectral Lines in the Atmosphere of Hot Stars**

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### **Authors' contributions**

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## **ABSTRACT**

The electron-impact broadening parameters of ion lines are of interest for a number of problems in astrophysical, laboratory, and technological plasma investigations. Singly ionized Iridium lines are confirmed their presence in stellar spectra of the chemically peculiar stars. Our calculations are performed using the modified semiempirical method of Dimitrijević and Konjević. Stark widths for 301 Ir II spectral lines are presented. From the calculated list of lines, the 21 strongest lines from the iridium spectrum are selected with high value of intensity  $\geq 3000$  to demonstrate importance of the Stark broadening mechanism for different types of stars. The analysis of the electron-impact effect on spectral line shapes are performed and obtained Stark and Doppler widths are compared.

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## 1 INTRODUCTION

The chemically peculiar (CP) stars of the upper main sequence, usually it has been classified as Bp, Ap, HgMn, or Am type of stars. Spectroscopy of these CP stars plays important role for resolving the elemental abundances and physical processes in their atmospheres. Today's satellite spectroscopy provides high-resolution spectra, making heavy elements very important and available for research in astrophysics. In [1] it is noted Goddard High Resolution Spectrograph (GHRS) on board the Hubble Space Telescope at an average resolution of 0.023 Å. GHRS observations of  $\chi$  Lupi have become a useful source of data for atomic spectroscopy, displaying many transitions that are difficult to observe in a laboratory setting. This project has been successful in determining abundances for more than 50 elements. In [2] it is reported 4d-elements and 5d-elements in CP stars of Hg-Mn type and the interpretation of their spectra II and III.

Quantitatively accurate analysis and theoretical interpretation of the spectrum of CP stars requires available atomic data, wavelengths, transition probabilities, hyperfine structure and isotopic shifts for the lowest ionization states of many elements. The abundance of an element is a key parameter in the observability of spectral lines. Significance of these data for heavy and rare-earth elements (REE) in stellar spectra is increasing, as noted in [3, 4] where one can see that the REE are overabundant in CP stars. As atomic number increases, the cosmic abundance drops. Usually, as spectroscopic abundances from the solar photosphere become more reliable, they tend to confirm the meteoritic values [5, 6]. Chemical composition data for the Sun can be derived from very different layers, from the center to the outermost coronal layers.

Electron configuration of Iridium follows noble xenon gas [Xe]  $4f^{14}5d^76s^2$ . Iridium has two stable isotopes  $^{191}\text{Ir}$  and  $^{193}\text{Ir}$  with abundances of 37.3% and 62.7% and nuclear spins 3/2 [7].

The determination of abundance for osmium and iridium for  $\chi$  Lupi star has followed the techniques used in previous analyses performed in [8]. Since the observed spectrum is a combination of spectra from both stars of the binary system, a synthetic spectrum was generated for each star for short wavelength intervals that included each of the spectral lines studied.

In [9], it is presented experimentally determined wavelengths and oscillator strengths for 27 Os II and 23 Ir II transitions. The oscillator strengths have been determined by combining radiative lifetimes measured using the laser-induced fluorescence technique with branching fractions determined from Fourier transform spectrometer emission line intensities. This new data were used in a synthetic spectrum analysis of high-resolution ultraviolet spectra of  $\chi$  Lupi obtained with the Hubble Space Telescope. Weak abundance enhancements were determined for both elements,  $[\text{Os}/\text{H}] = +1.3$  dex and  $[\text{Ir}/\text{H}] = +0.7$  dex. In the case of iridium only one reasonably unblended line of Ir II was identified in stellar spectra [9]. Its analysis followed a similar method as for the lines of Os II. The fit to the line Ir II  $\lambda=2152.706$  Å is presented in their work, with the best fit abundance value of  $(\text{Ir}/\text{H}) = \log(\epsilon_{\text{Ir}}) - \log(\epsilon_{\text{H}}) = 2.05$ , on a scale where  $\log(\epsilon_{\text{H}})=12$ , representing an abundance enhancement of +0.7 dex with respect to the solar system.

Mentioned article was the main motivation for our work on iridium spectral lines. The presence of these lines in stellar plasma emphasized the need to know the parameters for Stark broadening. The atomic data of such rare elements have only become available recently. Our contribution is an effort to combine mentioned stellar processes with the pointing out a need for the experimental data and, as such, to open a path for more sophisticated spectroscopy with the help of the estimated Stark parameters.

The spectrum of Ir II has been measured in the wavelength region of approximately 1250 Å to 4750 Å. The ground level system is associated

with the electron configurations  $5d^8$ ,  $5d^76s$  and  $5d^66s^2$ , which are strongly mixed [10]. In this system 35 levels out of 81 were identified. The energy levels have been adjusted by least-squares level optimization using the LOPT code [11].

## 2 THEORETICAL METHOD

Theoretical method for calculations which is used here for Stark widths of Ir II spectral lines is based on the modified semiempirical method (MSE) [12], valid for the Stark broadening of isolated, non-hydrogenic ion lines. Here, we note more complex semi-empirical method [13] or the semi-classical perturbation method [14, 15]. In comparison with these methods MSE needs less atomic data. Therefore, it is more applicable in the case of more complex spectra of heavier elements such as iridium. Due to a very complex spectrum of Ir II it was not possible to adequately use the MSE approach, so we used the simplified version of this approach given in [16]

For all 301 calculated lines we used the energy levels obtained from NIST ADS databases [10, 11]. The matrix elements needed for the present calculations are obtained within the Coulomb approximation formalism [17], while the line and multiplet factors are taken from [18] whenever it is necessary.

In the case when more sophisticated methods are not applicable we can use approximate formula [19] which is simple and sometimes very useful in astrophysics, especially when data for a large number spectral lines are needed, and they are missing in existing literature and databases.

The accuracy of the MSE approximation used in the calculation of Stark broadening parameters is assumed to be about 50%. In the case of the emitters with very complex spectra (e.g., Xe II and Kr II) MSE approach gives a very good agreement with experimental measurements (in the interval 30%), see [20, 21].

## 3 RESULTS

The calculations of Stark widths (FWHM) for electron-impact broadening, have been performed for a perturber density of  $10^{17} \text{ cm}^{-3}$  and for a temperature value of 10000K, see Table 1. The order of transitions in our table follows the list of spectral lines from the NIST database, which made it easier to monitor and observe atomic data for spectroscopy. The transformation of Stark width in Å to the width expressed in angular frequency units may be performed using the following formula, see [3, 4]:

$$W(\text{Å}) = \frac{\lambda^2}{2\pi c} W(s^{-1}) \quad (3.1)$$

where  $c$  is the speed of light. For synthetic spectrum calculations it is more convenient to use following expression for the different temperatures:

$$W(s^{-1}) = A_0 T^{-1/2} \quad (3.2)$$

where  $A_0$  represent constant determined with the best fit, for details about this and following equation referred to [22]. In our Table 1. for all 301 spectral lines of iridium it is presented by columns: transition between levels, wavelength in Å, Full Width at Half Maximum in Å, and logarithmic form for Stark width per electron and temperature of 10000K noted with  $\log W$ .

For A-type stars the most representiv value for temperature is 10000K where the Stark broadening becomes the dominant pressure broadening mechanism due to hydrogen ionization. In many cases there is a good approximation with next expression.

$$W_o = (T/T_o)^{-1/2} W_{T_o} \quad (3.3)$$

where  $W_{T_o}$  represent Stark width at  $T_o=10000\text{K}$ . With this we can obtained Stark width at any value of temperatures from 10 000 K to 300 000 K.

Table 1. Calculated parameters for Ir II spectral lines

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^8\ ^3F_4 - 6548_3^o$	1581.8	0.0076	-6.241
$5d^7(^4F)6s\ ^5F_5 - 6273_4^o$	1594.0	0.0268	-5.702
$5d^8\ ^3P_2 - 6580_3^o$	1594.5	0.0080	-6.226
$5d^8\ ^3P_2 - 6548_3^o$	1602.8	0.0078	-6.242
$5d^7(^4F)6s\ ^5F_4 - 6690_3^o$	1609.8	0.0317	-5.638
$5d^7(^4F)6s\ ^5F_5 - 6197_5^o$	1613.7	0.0269	-5.711
$5d^8\ ^3P_2 - 6420_3^o$	1636.2	0.0070	-6.307
$5d^7(^4F)6s\ ^5F_4 - 6548_3^o$	1647.6	0.0318	-5.656
$5d^8\ ^3P_2 - 6376_2^o$	1648.1	0.0067	-6.332
$5d^8\ ^3F_4 - 6273_4^o$	1653.7	0.0059	-6.391
$5d^8\ ^3F_4 - 6197_5^o$	1674.8	0.0054	-6.440
$5d^8\ ^3F_4 - 6148_4^o$	1688.4	0.0051	-6.473
$5d^8\ ^1D_2 - 6690_3^o$	1726.1	0.0105	-6.177
$5d^7(^4F)6s\ ^5F_3 - 6580_2^o$	1735.6	0.0363	-5.644
$5d^8\ ^3P_2 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	1747.5	0.0044	-6.563
$5d^7(^4F)6s\ ^5F_4 - 6197_5^o$	1748.8	0.0324	-5.700
$5d^8\ ^3P_1 - 6580_2^o$	1762.3	0.0097	-6.228
$5d^8\ ^1D_2 - 6548_3^o$	1769.7	0.0095	-6.244
$5d^7(^4F)6s\ ^5F_3 - 6454_3^o$	1774.5	0.0366	-5.660
$5d^7(^4F)6s\ ^5F_5 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	1778.3	0.0279	-5.779
$5d^8\ ^3P_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	1784.3	0.0036	-6.669
$5d^8\ ^1G_4 - 7311_4^o$	1788.9	0.0199	-5.931
$5d^7(^4F)6s\ ^3F_4 - 6678_5^o$	1816.0	0.0417	-5.623
$5d^8\ ^3F_3 - 6454_3^o$	1831.1	0.0091	-6.293
$5d^7(^4F)6s\ ^5F_2 - 6580_2^o$	1834.9	0.0413	-5.636
$5d^8\ ^3F_3 - 6420_3^o$	1842.3	0.0088	-6.311
$5d^8\ ^3P_0 - 6520_2^o$	1852.2	0.0100	-6.259
$5d^8\ ^3F_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	1852.8	0.0015	-7.090
$5d^7(^4F)6s\ ^5F_1 - 6580_2^o$	1857.1	0.0425	-5.635
$5d^8\ ^3F_3 - 6376_2^o$	1857.4	0.0085	-6.335
$5d^66s^2\ ^5D_4 - 7311_4^o$	1857.7	0.0551	-5.521
$5d^7(^4F)6s\ ^5F_5 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_5^o$	1862.5	0.0287	-5.808
$5d^7(^4F)6s\ ^5F_5 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_4^o$	1868.3	0.0287	-5.809
$5d^7(^4F)6s\ ^3F_4 - 6516_5^o$	1870.9	0.0423	-5.643
$5d^7(^4F)6s\ ^5F_3 - 6148_4^o$	1876.1	0.0376	-5.697
$5d^7(^4F)6s\ ^5F_1 - 6520_1^o$	1878.1	0.0427	-5.642
$5d^7(^4F)6s\ ^5F_2 - 6454_3^o$	1878.5	0.0418	-5.652
$5d^7(^4P)6s\ ^5P_3 - 6580_2^o$	1883.6	0.0439	-5.633
$5d^7(^4F)6s\ ^5F_2 - 6420_3^o$	1890.3	0.0419	-5.656
$5d^7(^4F)6s\ ^5F_2 - 6376_2^o$	1906.3	0.0421	-5.661
$5d^7(^4F)6s\ ^5F_5 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_5^o$	1948.1	0.0296	-5.833
$5d^7(^4P)6s\ ^5P_3 - 6376_2^o$	1958.8	0.0449	-5.657
$5d^8\ ^3P_2 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	1976.7	0.0330	-5.798
$5d^8\ ^3F_3 - 6046_2^o$	1978.9	0.0058	-6.557
$5d^7(^4F)6s\ ^5F_5 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_4^o$	1988.0	0.0301	-5.843

Table 1. Continued

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^7(^4F)6s\ ^3F_4 - 6197_5^o$	1990.0	0.0438	-5.681
$5d^7(^4F)6s\ ^5F_2 - 6147_3^o$	1993.4	0.0433	-5.688
$5d^8\ ^1D_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	1993.7	0.0044	-6.677
$5d^7(^4P)6s\ ^5P_2 - 6580_2^o$	1994.9	0.0502	-5.625
$5d^8\ ^3P_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	1995.8	0.0332	-5.804
$5d^8\ ^3P_1 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	1997.2	0.0045	-6.677
$5d^7(^2G)6s\ ^3G_3 - 7311_4^o$	2002.7	0.0656	-5.512
$5d^7(^4P)6s\ ^5P_2 - 6548_3^o$	2007.2	0.0503	-5.628
$5d^7(^4F)6s\ ^3F_4 - 6148_4^o$	2008.6	0.0441	-5.687
$5d^8\ ^1G_4 - 6690_3^o$	2011.5	0.0143	-6.176
$5d^8\ ^1G_4 - 6678_5^o$	2016.5	0.0142	-6.181
$5d^7(^4P)6s\ ^5P_2 - 6520_1^o$	2018.5	0.0505	-5.632
$5d^8\ ^3F_2 - 6690_3^o$	2019.7	0.0145	-6.175
$5d^8\ ^3P_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2022.8	0.0336	-5.811
$5d^7(^4F)6s\ ^3F_3 - 6690_3^o$	2023.2	0.0538	-5.606
$5d^66s^2\ ^5D_3 - 7311_4^o$	2024.3	0.0672	-5.510
$5d^8\ ^1D_2 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2027.3	0.0037	-6.770
$5d^7(^2G)6s\ ^3G_5 - 6678_5^o$	2027.5	0.0539	-5.608
$5d^7(^4F)6s\ ^5F_4 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2028.7	0.0355	-5.789
$5d^8\ ^3F_3 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2031.7	0.0046	-6.677
$5d^8\ ^3P_0 - 5d^7(^4P_{1/2})6p\ (1/2,1/2)_1^o$	2033.5	0.0060	-6.565
$5d^7(^4F)6s\ ^5F_2 - 6046_2^o$	2033.8	0.0439	-5.700
$5d^8\ ^3F_4 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_5^o$	2037.2	0.0329	-5.826
$5d^7(^2G)6s\ ^3G_5 - 6654_4^o$	2037.4	0.0540	-5.611
$5d^7(^4F)6s\ ^5F_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_5^o$	2044.2	0.0357	-5.793
$5d^8\ ^3P_2 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_1^o$	2044.8	0.0339	-5.816
$5d^7(^4P)6s\ ^5P_3 - 6148_4^o$	2049.6	0.0462	-5.684
$5d^7(^4P)6s\ ^5P_3 - 6147_3^o$	2050.2	0.0462	-5.684
$5d^7(^4F)6s\ ^5F_4 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_4^o$	2051.2	0.0358	-5.795
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2057.2	0.0448	-5.700
$5d^7(^4F)6s\ ^5F_1 - 5d^66s(^6D_{1/2})6p\ (1/2,1/2)_0^o$	2058.9	0.0452	-5.697
$5d^7(^4F)6s\ ^5F_3 - 5664_2^o$	2063.0	0.0401	-5.751
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4P_{1/2})6p\ (1/2,1/2)_1^o$	2064.8	0.0453	-5.699
$5d^7(^4F)6s\ ^5F_4 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2065.1	0.0360	-5.798
$5d^8\ ^3F_2 - 6580_2^o$	2065.8	0.0134	-6.227
$5d^7(^4F)6s\ ^3F_3 - 6580_2^o$	2069.5	0.0546	-5.619
$5d^8\ ^3P_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2070.5	0.0342	-5.823
$5d^8\ ^1G_4 - 6548_3^o$	2070.9	0.0130	-6.243
$5d^7(^4F)6s\ ^3F_3 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2075.4	0.0403	-5.754
$5d^8\ ^3P_2 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_3^o$	2076.8	0.0343	-5.824
$5d^7(^2H)6s\ ^3H_5 - 7311_4^o$	2078.4	0.0714	-5.507
$5d^7(^4P)6s\ ^5P_2 - 6376_2^o$	2078.8	0.0515	-5.649
$5d^8\ ^3F_2 - 6548_3^o$	2079.7	0.0131	-6.243
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2080.6	0.0403	-5.755
$5d^8\ ^3F_4 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_4^o$	2081.0	0.0335	-5.836
$5d^7(^4F)6s\ ^3F_3 - 6548_3^o$	2083.4	0.0549	-5.623

Table 1. Continued

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^7(^4P)6s\ ^3P_2 - 6690_3^o$	2084.2	0.0577	-5.602
$5d^8\ ^1G_4 - 6516_5^o$	2084.5	0.0127	-6.259
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2090.3	0.0448	-5.714
$5d^8\ ^3P_1 - 5d^7(^4P_{1/2})6p\ (1/2,1/2)_0^o$	2090.8	0.0024	-6.979
$5d^8\ ^3F_2 - 6520_1^o$	2091.9	0.0129	-6.257
$5d^7(^4P)6s\ ^5P_3 - 6046_2^o$	2093.8	0.0469	-5.695
$5d^7(^2G)6s\ ^3G_5 - 6516_5^o$	2096.2	0.0551	-5.627
$5d^8\ ^1D_2 - 5664_2^o$	2097.1	0.0022	-7.023
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2097.3	0.0406	-5.760
$5d^66s^2\ ^5D_4 - 6690_3^o$	2098.8	0.0586	-5.601
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2100.2	0.0471	-5.697
$5d^8\ ^3P_1 - 5664_2^o$	2101.0	0.0022	-7.023
$5d^66s^2\ ^5D_4 - 6678_5^o$	2104.3	0.0587	-5.602
$5d^8\ ^1D_2 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2110.0	0.0019	-7.086
$5d^8\ ^1G_4 - 6454_3^o$	2112.2	0.0121	-6.291
$5d^8\ ^3P_1 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2113.9	0.0019	-7.086
$5d^8\ ^1D_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2115.0	0.0018	-7.112
$5d^8\ ^3P_1 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2118.9	0.0018	-7.112
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2119.1	0.0462	-5.712
$5d^8\ ^3F_2 - 6454_3^o$	2121.3	0.0122	-6.291
$5d^8\ ^3P_0 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2123.6	0.0041	-6.771
$5d^7(^4F)6s\ ^3F_3 - 6454_3^o$	2125.1	0.0556	-5.634
$5d^7(^4F)6s\ ^5F_5 - 5d^7(^4F_{9/2})6p\ (9/2,1/2)_5^o$	2126.8	0.0319	-5.877
$5d^8\ ^1G_4 - 6420_3^o$	2127.1	0.0118	-6.309
$5d^7(^4F)6s\ ^5F_2 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2127.9	0.0454	-5.724
$5d^8\ ^1D_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2132.5	0.0015	-7.218
$5d^7(^2D_2)6s\ ^3D_3 - 7311_4^o$	2139.8	0.0764	-5.503
$5d^8\ ^3F_3 - 5664_2^o$	2139.9	0.0023	-7.024
$5d^7(^2G)6s\ ^3G_4 - 6690_3^o$	2144.6	0.0616	-5.598
$5d^7(^4F)6s\ ^5F_4 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_5^o$	2147.8	0.0373	-5.817
$5d^7(^4P)6s\ ^3P_2 - 6548_3^o$	2148.2	0.0589	-5.619
$5d^7(^4P)6s\ ^5P_1 - 6520_1^o$	2148.7	0.0584	-5.623
$5d^7(^4F)6s\ ^5F_4 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_3^o$	2152.7	0.0374	-5.819
$5d^8\ ^3F_2 - 6376_2^o$	2156.7	0.0115	-6.333
$5d^7(^4F)6s\ ^3F_3 - 6376_2^o$	2160.7	0.0563	-5.643
$5d^7(^4P)6s\ ^3P_2 - 6520_1^o$	2161.1	0.0592	-5.622
$5d^66s^2\ ^5D_4 - 6548_3^o$	2163.7	0.0599	-5.618
$5d^66s^2\ ^5D_4 - 6516_5^o$	2178.5	0.0602	-5.622
$5d^7(^4F)6s\ ^5F_3 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2179.0	0.0420	-5.778
$5d^7(^4P)6s\ ^5P_2 - 6147_3^o$	2182.8	0.0535	-5.675
$5d^7(^4P)6s\ ^3P_2 - 6454_3^o$	2192.5	0.0598	-5.630
$5d^8\ ^1G_4 - 6273_4^o$	2196.0	0.0103	-6.394
$5d^7(^4F)6s\ ^5F_4 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_4^o$	2196.4	0.0381	-5.828
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	2197.5	0.0423	-5.782
$5d^7(^4P)6s\ ^3P_1 - 6580_2^o$	2203.7	0.0632	-5.611

Table 1. Continued

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_4^o$	2204.9	0.0425	-5.784
$5d^7(^4F)6s\ ^5F_2 - 5664_2^o$	2205.0	0.0468	-5.741
$5d^7(^4P)6s\ ^3P_2 - 6420_3^o$	2208.6	0.0602	-5.634
$5d^66s^2\ ^5D_4 - 6454_3^o$	2208.7	0.0609	-5.629
$5d^7(^2G)6s\ ^3G_5 - 6273_4^o$	2209.0	0.0573	-5.655
$5d^7(^4F)6s\ ^3F_3 - 6273_4^o$	2210.0	0.0574	-5.655
$5d^7(^2G)6s\ ^3G_4 - 6548_3^o$	2212.3	0.0631	-5.615
$5d^8\ ^1D_2 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2217.1	0.0437	-5.776
$5d^7(^4P)6s\ ^5P_1 - 6376_2^o$	2217.2	0.0598	-5.640
$5d^7(^4F)6s\ ^5F_2 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2219.2	0.0471	-5.744
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2221.1	0.0428	-5.787
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2224.8	0.0472	-5.745
$5d^66s^2\ ^5D_4 - 6420_3^o$	2225.0	0.0612	-5.633
$5d^7(^2G)6s\ ^3G_4 - 6516_5^o$	2227.8	0.0634	-5.618
$5d^7(^4P)6s\ ^3P_2 - 6376_2^o$	2230.4	0.0607	-5.639
$5d^7(^4P)6s\ ^5P_2 - 6046_2^o$	2232.3	0.0545	-5.686
$5d^7(^4P)6s\ ^3P_1 - 6520_1^o$	2233.4	0.0639	-5.618
$5d^8\ ^1G_4 - 6197_5^o$	2233.4	0.0095	-6.443
$5d^8\ ^3F_4 - 5d^7(^4F_{9/2})6p\ (9/2,1/2)_5^o$	2234.4	0.0358	-5.869
$5d^8\ ^1D_2 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	2236.3	0.0441	-5.780
$5d^7(^4P)6s\ ^5P_2 - 5d^7(^4P_{1/2})6p\ (1/2,1/2)_1^o$	2236.6	0.0546	-5.687
$5d^7(^4F)6s\ ^5F_1 - 5664_2^o$	2237.1	0.0485	-5.739
$5d^7(^4P)6s\ ^5P_2 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2239.6	0.0547	-5.688
$5d^8\ ^3P_1 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	2240.6	0.0443	-5.779
$5d^7(^4F)6s\ ^5F_5 - 5d^7(^4F_{9/2})6p\ (9/2,1/2)_4^o$	2242.7	0.0336	-5.900
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2244.2	0.0476	-5.749
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2245.7	0.0483	-5.744
$5d^7(^2G)6s\ ^3G_5 - 6197_5^o$	2246.9	0.0582	-5.664
$5d^7(^4F)6s\ ^3F_2 - 6690_3^o$	2249.5	0.0688	-5.591
$5d^7(^4F)6s\ ^5F_1 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2251.7	0.0488	-5.742
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2255.5	0.0434	-5.794
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2257.5	0.0489	-5.743
$5d^8\ ^1G_4 - 6148_4^o$	2257.7	0.0090	-6.476
$5d^8\ ^1G_4 - 6147_3^o$	2258.5	0.0090	-6.478
$5d^7(^2G)6s\ ^3G_4 - 6454_3^o$	2259.4	0.0642	-5.626
$5d^8\ ^1D_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2260.7	0.0446	-5.785
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2265.2	0.0486	-5.748
$5d^8\ ^3F_2 - 6147_3^o$	2268.9	0.0091	-6.477
$5d^7(^2G)6s\ ^3G_5 - 6148_4^o$	2271.4	0.0587	-5.669
$5d^7(^4F)6s\ ^3F_3 - 6148_4^o$	2272.5	0.0588	-5.669
$5d^7(^4F)6s\ ^3F_3 - 6147_3^o$	2273.3	0.0588	-5.669
$5d^7(^4P)6s\ ^5P_3 - 5664_2^o$	2275.7	0.0504	-5.737
$5d^7(^2G)6s\ ^3G_4 - 6420_3^o$	2276.5	0.0646	-5.629
$5d^8\ ^3F_3 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	2285.0	0.0464	-5.776
$5d^7(^2G)6s\ ^3G_3 - 6690_3^o$	2286.9	0.0715	-5.589

Table 1. Continued

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^7(^4P)6s\ ^5P_3 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2290.8	0.0508	-5.740
$5d^8\ ^3F_3 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_4^o$	2293.0	0.0465	-5.778
$5d^8\ ^1D_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2296.3	0.0452	-5.791
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2297.1	0.0509	-5.741
$5d^8\ ^3P_1 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2300.9	0.0455	-5.791
$5d^7(^4F)6s\ ^3F_2 - 6580_2^o$	2306.8	0.0703	-5.604
$5d^7(^4P)6s\ ^3P_1 - 6376_2^o$	2307.4	0.0657	-5.634
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2314.9	0.0445	-5.805
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2317.4	0.0513	-5.745
$5d^8\ ^3F_2 - 6046_2^o$	2322.3	0.0080	-6.554
$5d^7(^4F)6s\ ^5F_3 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_3^o$	2322.7	0.0447	-5.807
$5d^7(^4F)6s\ ^3F_2 - 6548_3^o$	2324.1	0.0707	-5.608
$5d^8\ ^1D_2 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_1^o$	2324.7	0.0458	-5.797
$5d^7(^4F)6s\ ^3F_3 - 6046_2^o$	2327.0	0.0600	-5.680
$5d^8\ ^3P_1 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_1^o$	2329.4	0.0460	-5.796
$5d^7(^4F)6s\ ^3F_3 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2334.9	0.0602	-5.682
$5d^7(^4F)6s\ ^5F_2 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2338.0	0.0495	-5.768
$5d^7(^4F)6s\ ^3F_2 - 6520_1^o$	2339.3	0.0711	-5.611
$5d^66s^2\ ^5D_4 - 6197_5^o$	2341.7	0.0640	-5.658
$5d^7(^4P)6s\ ^5P_2 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2346.1	0.0571	-5.709
$5d^7(^2G)6s\ ^3G_3 - 6580_2^o$	2346.1	0.0571	-5.709
$5d^7(^4P)6s\ ^3P_2 - 6147_3^o$	2350.6	0.0635	-5.664
$5d^7(^2G)6s\ ^3G_4 - 6273_4^o$	2355.6	0.0666	-5.646
$5d^8\ ^1D_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2357.9	0.0465	-5.803
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	2359.4	0.0500	-5.772
$5d^7(^4F)6s\ ^3F_4 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2360.7	0.0507	-5.766
$5d^8\ ^3F_4 - 5d^7(^4F_{9/2})6p\ (9/2,1/2)_4^o$	2362.6	0.0380	-5.892
$5d^8\ ^3P_1 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2362.8	0.0467	-5.802
$5d^8\ ^1D_2 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_3^o$	2366.1	0.0467	-5.804
$5d^7(^4F)6s\ ^5F_4 - 5d^7(^4F_{9/2})6p\ (9/2,1/2)_5^o$	2368.0	0.0411	-5.860
$5d^66s^2\ ^5D_4 - 6148_4^o$	2368.3	0.0647	-5.663
$5d^66s^2\ ^5D_4 - 6147_3^o$	2369.2	0.0647	-5.663
$5d^66s^2\ ^5D_3 - 6580_2^o$	2375.8	0.0752	-5.600
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_5^o$	2381.8	0.0511	-5.770
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2386.6	0.0506	-5.776
$5d^7(^4P)6s\ ^5P_1 - 5d^66s(^6D_{1/2})6p\ (1/2,1/2)_0^o$	2389.6	0.0640	-5.676
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_4^o$	2391.3	0.0513	-5.772
$5d^7(^4P)6s\ ^5P_1 - 6046_2^o$	2392.6	0.0641	-5.676
$5d^7(^2H)6s\ ^3H_5 - 6678_5^o$	2393.1	0.0791	-5.585
$5d^66s^2\ ^5D_3 - 6548_3^o$	2394.2	0.0758	-5.604
$5d^7(^4F)6s\ ^3F_2 - 6420_3^o$	2395.0	0.0726	-5.622
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_2^o$	2396.2	0.0518	-5.769
$5d^8\ ^3F_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2396.2	0.0065	-6.673
$5d^7(^2G)6s\ ^3G_4 - 6197_5^o$	2398.7	0.0677	-5.654
$5d^7(^4F)6s\ ^3F_3 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2401.2	0.0619	-5.694



Table 1. Continued

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^7(^2F)6s\ ^3F_3 - 7311_4^o$	2403.6	0.0998	-5.488
$5d^7(^2H)6s\ ^3H_5 - 6654_6^o$	2407.0	0.0795	-5.588
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2410.2	0.0518	-5.775
$5d^7(^4P)6s\ ^3P_2 - 5d^7(^4P_{1/2})6p\ (1/2,1/2)_1^o$	2413.1	0.0652	-5.676
$5d^7(^4P)6s\ ^3P_2 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2416.6	0.0653	-5.677
$5d^7(^4P)6s\ ^5P_3 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2417.6	0.0536	-5.763
$5d^66s^2\ ^5D_2 - 6690_3^o$	2417.9	0.0814	-5.581
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2426.3	0.0515	-5.783
$5d^7(^2G)6s\ ^3G_4 - 6148_4^o$	2426.7	0.0685	-5.660
$5d^7(^2G)6s\ ^3G_4 - 6147_3^o$	2427.6	0.0685	-5.660
$5d^66s^2\ ^5D_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2436.2	0.0665	-5.676
$5d^7(^4P)6s\ ^5P_2 - 5664_2^o$	2440.2	0.0594	-5.726
$5d^8\ ^3F_2 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2445.8	0.0055	-6.765
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_4^o$	2449.6	0.0543	-5.768
$5d^8\ ^3P_0 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_1^o$	2452.3	0.0519	-5.789
$5d^7(^4P)6s\ ^5P_2 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2457.6	0.0598	-5.729
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_1^o$	2458.0	0.0522	-5.788
$5d^7(^4P)6s\ ^5P_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2464.4	0.0600	-5.730
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2465.2	0.0534	-5.781
$5d^7(^2D)6s\ ^3D_3 - 6690_3^o$	2467.3	0.0853	-5.579
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2469.5	0.0548	-5.771
$5d^8\ ^3F_3 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_4^o$	2476.1	0.0505	-5.810
$5d^66s^2\ ^5D_2 - 6580_2^o$	2484.2	0.0834	-5.594
$5d^7(^4P)6s\ ^3P_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2487.5	0.0672	-5.689
$5d^7(^4P)6s\ ^5P_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2488.3	0.0606	-5.734
$5d^7(^2H)6s\ ^3H_5 - 6516_5^o$	2489.5	0.0820	-5.603
$5d^7(^4P)6s\ ^3P_1 - 5d^66s(^6D_{1/2})6p\ (1/2,1/2)_0^o$	2494.8	0.0707	-5.669
$5d^7(^4F)6s\ ^5F_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2495.2	0.0531	-5.794
$5d^66s^2\ ^5D_3 - 6376_2^o$	2496.9	0.0788	-5.623
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4F_{3/2})6p\ (3/2,1/2)_1^o$	2498.0	0.0542	-5.786
$5d^7(^4P)6s\ ^3P_1 - 6046_2^o$	2498.0	0.0708	-5.670
$5d^7(^2G)6s\ ^3G_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2498.0	0.0705	-5.672
$5d^66s^2\ ^5D_2 - 6548_3^o$	2504.4	0.0841	-5.598
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_2^o$	2512.1	0.0558	-5.778
$5d^7(^4F)6s\ ^5F_4 - 5d^7(^4F_{9/2})6p\ (9/2,1/2)_4^o$	2512.6	0.0440	-5.882
$5d^7(^2H)6s\ ^3H_6 - 6197_6^o$	2517.9	0.0758	-5.648
$5d^7(^4F)6s\ ^3F_4 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_5^o$	2523.6	0.0544	-5.793
$5d^7(^4P)6s\ ^5P_1 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2523.9	0.0676	-5.699
$5d^7(^2G)6s\ ^3G_3 - 6273_4^o$	2528.4	0.0785	-5.636
$5d^7(^4F)6s\ ^3F_4 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_3^o$	2530.4	0.0546	-5.794
$5d^7(^2D)6s\ ^3D_3 - 6580_2^o$	2536.4	0.0875	-5.591
$5d^7(^4F)6s\ ^5F_1 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2536.4	0.0551	-5.792
$5d^8\ ^3F_2 - 5664_2^o$	2548.2	0.0033	-7.015
$5d^7(^4F)6s\ ^3F_3 - 5664_2^o$	2553.8	0.0660	-5.720
$5d^7(^2D)6s\ ^3D_3 - 6548_3^o$	2557.4	0.0883	-5.595

Table 1. Continued

Transition	$\lambda(\text{\AA})$	FWHM( $\text{\AA}$ )	logW
$5d^8\ ^1G_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2561.8	0.0027	-7.105
$5d^7(^4F)6s\ ^3F_2 - 6147_3^o$	2562.9	0.0777	-5.652
$5d^7(^4F)6s\ ^3F_3 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2572.9	0.0665	-5.723
$5d^8\ ^3F_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2574.7	0.0028	-7.102
$5d^7(^2G)6s\ ^3G_5 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2579.5	0.0667	-5.724
$5d^7(^4F)6s\ ^3F_3 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2580.9	0.0668	-5.724
$5d^7(^4P)6s\ ^3P_1 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_2^o$	2583.7	0.0734	-5.684
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_2^o$	2586.1	0.0577	-5.789
$5d^8\ ^1G_4 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2587.1	0.0022	-7.206
$5d^7(^4F)6s\ ^3F_4 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_4^o$	2591.0	0.0561	-5.803
$5d^7(^4P)6s\ ^5P_3 - 5d^7(^4F_{7/2})6p\ (7/2,1/2)_3^o$	2595.8	0.0580	-5.790
$5d^8\ ^3F_2 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2600.7	0.0022	-7.205
$5d^7(^4P)6s\ ^5P_2 - 5d^66s(^6D_{7/2})6p\ (7/2,1/2)_3^o$	2604.1	0.0637	-5.752
$5d^7(^4F)6s\ ^3F_3 - 5d^7(^4F_{5/2})6p\ (5/2,1/2)_3^o$	2606.6	0.0675	-5.728
$5d^7(^2G)6s\ ^3G_3 - 6148_4^o$	2610.5	0.0811	-5.649
$5d^7(^4P)6s\ ^5P_1 - 5d^7(^4P_{1/2})6p\ (1/2,1/2)_0^o$	2617.1	0.0704	-5.713
$5d^7(^4P)6s\ ^5P_1 - 5664_2^o$	2633.0	0.0709	-5.715
$5d^7(^4P)6s\ ^3P_1 - 5d^66s(^6D_{3/2})6p\ (3/2,1/2)_1^o$	2641.5	0.0752	-5.692
$5d^7(^4F)6s\ ^3F_2 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2641.5	0.0802	-5.664
$5d^7(^2H)6s\ ^3H_5 - 6273_4^o$	2650.1	0.0875	-5.630
$5d^7(^4P)6s\ ^3P_2 - 5664_2^o$	2651.8	0.0720	-5.714
$5d^7(^4P)6s\ ^5P_1 - 5d^66s(^6D_{5/2})6p\ (5/2,1/2)_2^o$	2653.3	0.0715	-5.718
$5d^7(^4P)6s\ ^5P_3 - 5d^66s(^6D_{9/2})6p\ (9/2,1/2)_4^o$	2659.7	0.0596	-5.799
$5d^7(^4P)6s\ ^5P_1 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2661.3	0.0717	-5.719
$5d^7(^4P)6s\ ^5P_2 - 5d^7(^4P_{5/2})6p\ (5/2,1/2)_3^o$	2664.5	0.0654	-5.760
$5d^7(^4P)6s\ ^3P_2 - 5d^7(^4P_{3/2})6p\ (3/2,1/2)_1^o$	2680.4	0.0729	-5.718
$5d^7(^2G)6s\ ^3G_3 - 6046_2^o$	2682.7	0.0836	-5.660
$5d^7(^2G)6s\ ^3G_3 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_3^o$	2693.3	0.0839	-5.662
$5d^7(^2H)6s\ ^3H_5 - 6197_5^o$	2704.9	0.0895	-5.638
$5d^66s\ ^5D_4 - 5d^7(^4F_{9/2})6p\ (9/2,3/2)_4^o$	2705.2	0.0745	-5.717

In [9], it is reported several lines of singly ionized iridium in the spectrum of  $\chi$  Lupi. Many of them are blended so therefore there are difficulties to isolate one of them. In the case of iridium only one reasonably unblended line of Ir II was identified 2152.7 Å. In this contribution to the study of  $\chi$  Lupi they used new accurate wavelengths and oscillator strengths from laboratory experiments for select lines of Os II and Ir II. In Fig. 1, we have shown the dependence for the Stark widths of temperatures calculated by the MSE method. We chosen two strongest lines from Ir II spectra: 2152.7 Å with relative intensity 8700 and very close 2242.7 Å with relative intensity 8000. One can see, as the temperature increases, the value for the Stark widths decreases, as usual. This is due to the line width formula [12] that depends reciprocally on the root temperature.

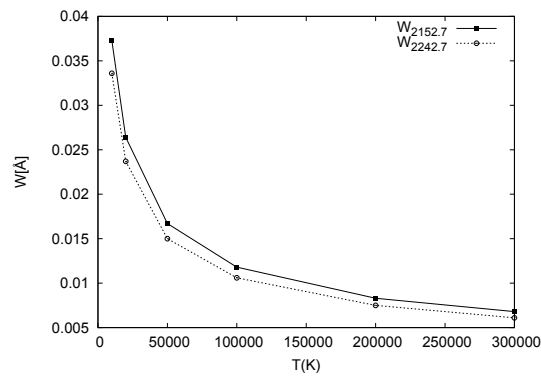
We have synthesized the line profiles of 21 Ir II strongest lines using SYNTH code [23] and the ATLAS9 code for stellar atmosphere models [24, 25] in the temperature range of  $6000 \leq T_{eff} \leq 16,000$  K, and  $4.0 \leq \log g \leq 5.0$ . For calculations with SYNTH code we need logarithmic values of Stark widths expressed in  $rad s^{-1}$  per electron for  $T = 10,000$  K. Also, for the spectrum synthesis parameter  $A_0$  is very useful and can be obtained from corresponding values of  $\log(A_0)$ . In the case of 2152.7 Å we used  $\log A_0 = -0.49986$  where  $A_0 = 4.81915$ .

We have analyzed the influence of electron-impact broadening mechanism on width ratio for 21 Ir II strongest lines. In our spectrum synthesis we used Solar value for iridium abundance - 10.69. This is a much smaller value than represent in [9], but it is usefull for all stellar atmospheres where the presence of iridium varies between these values. In Fig. 2. we can notice for Ir II 2152.7 Å that the ratio of Stark and Doppler width increases with increasing temperature. The rate of change for widths is highest in the stellar atmospheres with an effective temperature of 6000 Kelvins. In this case we used generally for all lines parameter values for surface gravity  $\log g = 4$  and turbulent velocity  $v_{turb} = 2$  km/s. For this considered line,

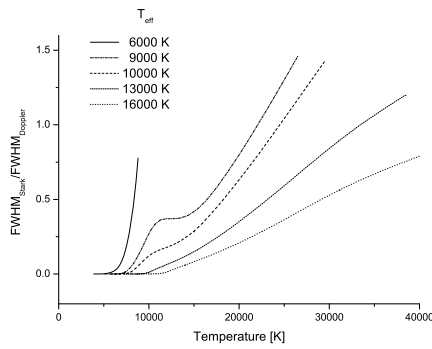
Stark broadening is more dominant than Doppler ones in all cases when the ratio of changes is greater than 1.

We have extended our analyzes of the strongest Ir II lines to test the dependence on the optical depth of the stellar atmosphere. One can see from Fig. 3. width ratio can be higher in the stars with high value of surface gravity. Especially for  $\log g = 5$  we notice a higher slope of the curve and Stark broadening becomes more important than Doppler ones from -1 for the optical depth and it also points to deeper layers. As one can see from solid line and  $\log g = 4$  Stark broadening is more important in photospheric layers. In our model we used  $T_{eff} = 10000$  K and turbulent velocity  $v_{turb} = 2$  km/s. Finally, in Fig. 4 we see an almost linear dependence of the width ratio as a function of temperature when we have a variable turbulent velocity in the stellar model. Here the functional dependences are approximately the same so the differences are very small regardless of the value of the turbulent velocity. Stark broadening becomes more significant at higher temperatures in atmospheres where the temperature is above 25,000 Kelvins. In this model we took  $T_{eff} = 10000$  K and  $\log g = 4$ . For both Figs. 3 and 4 we can marked the point 1 on Y-axes, where above this point Stark broadening becomes more important than Doppler ones.

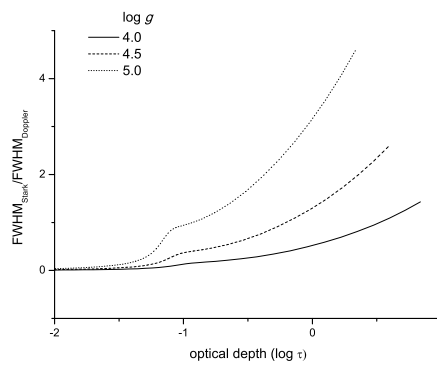
The experimental observation of the spectra of  $\chi$  Lupi presented in [9] is used in order to check the validity of the theoretically calculated data. The fitting procedure is not related to any synthetic solar spectra model, and presents a best effort fit of the observed spectra to estimate the Stark parameters of Ir II 2282.279. Since the fine structure of the line is not considered, in order to distinguish a Lorentzian and Gaussian component the Voigt profile is used for the fitting of the line. The fitted parameters of the Voigt profile for the Ir II 2282.279 Å line are 0.0134 for the Lorentzian and 0.0368 for the Gauss component of the profile. This result lies in the vicinity of the expected, theoretically calculated values for the Lorentzian component and for the Gaussian component of the line, see Fig. 5.



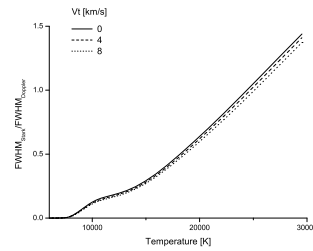
**Fig. 1.** Stark widths as a function of temperatures for singly ionized iridium spectral lines 2152.7 Å and 2242.7 Å spectral lines.



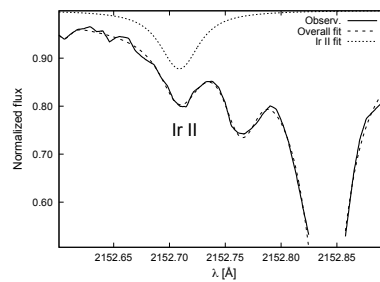
**Fig. 2.** Width ratio as a function of effective temperature,  $FWHM_{Stark}$  - Stark width and  $FWHM_{Doppler}$  - Doppler width, for the Ir II 2152.7 Å spectral line.



**Fig. 3.** Width ratio as a function of optical depth,  $FWHM_{Stark}$  - Stark width and  $FWHM_{Doppler}$  - Doppler width, for the Ir II 2152.7 Å spectral line.



**Fig. 4. Width ratio as a function of effective temperature,  $FWHM_{Stark}$  - Stark width and  $FWHM_{Doppler}$  - Doppler width, for the Ir II 2152.7 Å spectral line.**



**Fig. 5. From the observed spectrum of  $\chi$  Lupi presented in [9], the fitting procedure is used to extracted the Ir II 2152.7 Å line parameters assuming the Voigt line profile. The solid line presents experimental observation spectra, while the long dashed line is the overall fit, and short dash line is the sought line fit.**

## 4 CONCLUSION

The development of satellite spectroscopy has made available spectra of stars containing heavy elements and elements from the group of rare earths. In this paper, attention is focused to single ionized iridium, which is detected in the atmospheres of hot stars,  $\chi$  Lupi, so - called CP stars. This element whose energy levels have been determined for 301 known lines in the previous decade relatively recently. For calculation we chosen MSE method to obtain Stark widths of this singly ionized iridium. In our analysis we took a total of 21 strongest lines from the singly ionized iridium spectrum and whose intensities exceed the value of 3000. The Stark broadening mechanism is very important for A and B type of stellar atmospheres as well as for white dwarfs atmospheres, and one has to take into account this effect for investigations, analysis

and modeling of such stellar atmospheres. In terms of determining the equivalent width, the errors range between 10 % up to 45 %, so they are appropriate errors in determining abundance are similar.

The total number of 301 spectral lines of Ir II presented here is an extensive task, so we plan to continue research on another 172 lines from its spectrum whose intensities are much lower. This paper contributes to the formation of a database on the Stark broadening of ionized iridium spectral lines.

These calculations are useful for spectroscopy in further even more precise determination of the representation of heavy elements in stellar spectra as well as in laboratory and technological plasma.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

## REFERENCES

- [1] Leckrone David S, Proffitt Charles R, Wahlgren Glenn M, Johansson Sveneric G, Brage Tomas. Very High Resolution Ultraviolet Spectroscopy of a Chemically Peculiar Star: Results of the chi LUPi Pathfinder Project. *Astronomical Journal*. 1999;117(3):1454-1470.
- [2] Wyart JF, Raassen AJJ, Uylings PHM, Joshi YN. Spectra of high-Z ions of stellar interest. A theoretical study of (d+s)<sup>8</sup> mixed configurations in 5d- and 4d-elements. *Physica Scripta Volume T*. 1993;47:59-64.
- [3] Popović L. Č, Dimitrijević MS, Ryabchikova T. The electron-impact broadening effect in CP stars: the case of La II, La II i, EU II, and EU II i lines. *Astronomy and Astrophysics*. 1999;350:719-724.
- [4] Popović LČ, Simić S, Milovanović N, Dimitrijević MS. Stark Broadening Effect in Stellar Atmospheres: Nd II Lines. *The Astrophysical Journal Supplement Series*. 2001;135(1):109114.
- [5] Grevesse N, Sauval AJ. Standard Solar Composition. *Space Science Reviews*. 1998;85: 161-174.
- [6] Grevesse N, Sauval AJ. Abundances of the Elements in the Sun. In O. Manuel editor, *Origin of Elements in the Solar System, Implications of Post-1957 Observations*. 2000;261.
- [7] Xu HL, Svanberg S, Quinet P, Palmeri P, Biémont É. Improved atomic data for iridium atom (Ir I) and ion (Ir II) and the solar content of iridium. *Journal of Quantitative Spectroscopy and Radiative Transfer*. 2007;104(1):52-70.
- [8] Wahlgren Glenn M, Leckrone David S, Johansson Sveneric G, Rosberg Maria, Brage Tomas. The Abundances of Pt, Au, and HG in the Chemically Peculiar HgMn-Type Stars kappa CANCRI and chi LUPi. *Astrophysical Journal, Supplement*. 1995;444:438.
- [9] Ivarsson S, Wahlgren GM, Dai Z, Lundberg H, Leckrone DS. Constraining the very heavy elemental abundance peak in the chemically peculiar star  $\chi$  Lupi, with new atomic data for Os II and Ir II. *Astronomy and Astrophysics*. 2004;425:353-360.
- [10] van Kleef Th. AM, Metsch BC. Term analysis of singly ionized iridium (Ir II). *Physica B+C*. 1978;95(2):251-265.
- [11] Kramida AE. The program LOPT for least-squares optimization of energy levels. *Computer Physics Communications*. 2011;182(2):419-434.
- [12] Dimitrijević MS, Konjević N. Stark widths of doubly- and triply-ionized atom lines. *Journal of Quantitative Spectroscopy and Radiative Transfer*. 1980;24(6):451-459.
- [13] Griem Hans R. Semiempirical Formulas for the Electron-Impact Widths and Shifts of Isolated Ion Lines in Plasmas. *Physical Review*. 1968;165(1):258-266.
- [14] Sahal-Bréchet S. Impact Theory of the Broadening and Shift of Spectral Lines due to Electrons and Ions in a Plasma. *Astronomy and Astrophysics*. 1969;1:91.
- [15] Sahal-Bréchet S. Impact Theory of the Broadening and Shift of Spectral Lines due to Electrons and Ions in a Plasma (Continued). *Astronomy and Astrophysics*. 1969;2: 322.
- [16] Dimitrijević MS, Konjević N. Simple estimates for Stark broadening of ion lines in stellar plasmas. *Astronomy and Astrophysics*. 1987;172(1-2):345-349.
- [17] Bates DR, Agnete Damgaard. The Calculation of the Absolute Strengths of Spectral Lines. *Philosophical Transactions of the Royal Society of London. Series*

- A, Mathematical and Physical Sciences. 1949;242(842):101-122.
- [18] Shore Bruce W, Menzel Donald H. Generalized Tables for the Calculation of Dipole Transition Probabilities. Astrophysical Journal, Supplement. 1965;12:187.
- [19] Cowley CR. An approximate Stark broadening formula for use in spectrum synthesis. The Observatory. 1971;91: 139-140.
- [20] Popović L Č, Dimitrijević MS. Stark broadening of heavy ion lines: As II, Br II, Sb II and I II. Physica Scripta. 1996;53:325.
- [21] Popović LČ, Dimitrijević MS. Stark broadening of Xe II lines. Astronomy and Astrophysics, Supplement. 1996; 116:359-365.
- [22] Milovanović N, Dimitrijević MS, Popović LČ, Simić Z. Importance of collisions with charged particles for stellar UV line shapes: Cd III. Astronomy and Astrophysics. 2004;417:375-380.
- [23] Piskunov NE. SYNTH - a code for rapid spectral synthesis. In Physics and Evolution of Stars: Stellar Magnetism. 1992;92.
- [24] Kurucz Robert. Atomic Data for Ca, Sc, Ti, V, Cr, Mn, Co, Fe and Ni. Atomic Data for Ca, Sc, Ti, V, Cr, Mn, Co, Fe and Ni. Kurucz CD-ROM No. 20 - 22. Cambridge. 1994;20-22.
- [25] Kurucz Robert. ATLAS9 Stellar Atmosphere Programs and 2 km/s grid. ATLAS9 Stellar Atmosphere Programs and 2 km/s grid. Kurucz CD-ROM No. 13. Cambridge. 1993;13.

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