Main spectral features of meteors studied using a terawatt-class high-power laser

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ABSTRACT

Context. Meteor spectra are commonly interpreted using data from databases and tables. Several studies have demonstrated very sophisticated calculations of elemental compositions of meteoroid bodies based on the computation of synthetic meteor spectra or on the spectral analysis of airglow plasma containing evaporated, atomized, and ionized meteoroid matter. However, considering accuracy, reliability of computations, lack of laboratory experimental data in this field, as well as the complicated physical structure of meteor plasma, such qualitative assignment or quantitative calculations are still extensively discussed in the scientific community. Even on the laboratory level, many studies have shown the high complexity of the acquisition and interpretation of the data that are recorded with techniques of emission spectroscopy that are in fashion and philosophy similar to the spectral analysis of meteor plasma, that is, detection and quantification of the elements that are ablated from complicated multicomponent matrices.

Aims. The current study is focused on the application of terawatt-class laser-induced breakdown spectroscopy (TC-LIBS) of real samples of chondritic meteorites. We recorded emission spectra with high resolution and high precision that contain spectral lines that are typical for real meteoric spectra. Experimental data were compiled in a form that is convenient for the meteoric spectra interpretation and calibration.

Methods. TC-LIBS was carried out by a high-power terawatt-class laser facility, the Prague Asterix Laser System (PALS). The spectra were simultaneously recorded by an echelle high-resolution spectrograph in the UV/VIS spectral ranges and by a low-resolution spectrograph that was used for real observation of meteor spectra. We also present calculated synthetic spectra based on data from the NIST atomic spectra database.

Results. We assembled etalon qualitative tables of major meteoric spectral features that can be used both for the spectral wavelength calibration of low-resolution observational instruments and for the exact interpretation of meteor spectra. The data are compared with real meteor spectra.

Key words. atomic data – meteorites, meteors, meteoroids

1. Introduction

Meteor observation and spectroscopy is a highly important astronomical discipline. To date, most observational data are interpreted theoretically, and experimental work is lacking in this field. An in-depth analysis of meteor spectra can be used for example for basic qualitative or quantitative elemental analyses and characterization of meteoroids and their parent bodies, i.e., asteroids and comets. Asteroids and comets are remnants of the protoplanetary disk that formed the planetesimals and planets. Therefore, meteorites allow us to discover details about the properties of this disk as well as its history, that is, the physical and chemical evolution of the solar system. However, even in

the rare cases when a piece of meteorite is found, the fundamental problem of linking specific meteorites to their parent bodies remains (interplanetary matter, asteroids, or comet nuclei). Most bodies are evaporated and completely disintegrated during their descent, and their emission spectra, measured using spectrographs, are the only record of their chemical composition. When the trajectory is recorded alongside with the emission spectrum and if chemical composition is correctly interpreted, these data can provide detailed information about the chemical properties of its source in interplanetary space. Determination of the elemental composition provided by emission spectra analysis of the plasma formed above the surface of the evaporated object (meteor) is practically similar to laboratory laser-induced

breakdown spectroscopy (LIBS) elemental spectral analysis. In our recent pilot studies, we focused on the application of the calibration-free LIBS method in the interpretation of meteor spectra and the calculation of the elemental composition of meteoroids (Ferus et al. 2017a, 2018a). The method has been identified as feasible, but relatively time-demanding computation is still necessary. Ciucci et al. (1999), Tognoni et al. (2010), Giacomo (2011), Dell’Aglia et al. (2014), Horzňáčková et al. (2014), Ozdín et al. (2015) and Takahashi et al. (2015) provided a LIBS chemical analysis of meteorites and identified many advantages of this method, such as the applicability for a real-time in situ analysis without any preceding treatment, preparation, or isolation. On the other hand, as concluded in Tognoni et al. (2010) and references therein, even if the LIBS method is operated under strictly laboratory controlled conditions, the emission intensity of a particular spectral line, which is the main factor that influences the quantitative analysis, depends not only on the physical parameters of the spectral transition and the quantity of the emitting element, but also on the matrix in which the element is embedded. This influence of the matrix means that calibration curves or matrix-matched standards are required, which are not available in some practical situations, including meteorite samples. A coincidence of spectral lines in multicomponent analysis also complicates or even renders impossible a qualitative analysis of the spectra when low-resolution data are used. Although several studies have been published by only a few experts, such as Borovička et al. (1999), Jenniskens (2007), and Madiedo et al. (2014, 2013a,b), it was Ferus et al. (2018b) who demonstrated that a qualitative and quantitative analysis of mainly high-quality emission spectra that are assigned to the most abundant class of ordinary chondrites is possible. Many spectra of meteors are still classified as “unusual” and difficult to interpret.

The simulation of the chemical and physical consequences analogous to plasma formed by hypervelocity meteoroids or asteroids entering the Earth’s atmosphere by terawatt-class laser introduces a novel experimental approach also in the research of meteor spectra. In the past two decades, our team demonstrated several experiments that mostly focused on the chemical transformations of the atmosphere or on the interaction with solid or liquid surfaces (Babánková et al. 2006a). Most studies have been focused on impact-induced synthesis of biomolecules (Šponer et al. 2016; Ferus et al. 2017b) such as canonical nucleobases in Ferus et al. (2012, 2014a,b, 2015, 2017b), sugars in Civiš et al. (2016a), and aminoacids in Civiš et al. (2004), or the transformation of atmospheric molecules on early terrestrial planets (Civiš et al. 2008) such as the formation or decay of prebiotic substances, for instance, formamide (Ferus et al. 2011), isocyanic acid (Ferus et al. 2018a), and the transformations of hydrogen cyanide (Ferus et al. 2017c), acetylene (Civiš et al. 2016b), methane (Civiš et al. 2017), or carbon monoxide (Civiš et al. 2008; Ferus et al. 2009). Pyrometric measurement of dielectric breakdown induced by high-power terawatt-class lasers in the gas phase has shown that air-glow temperatures of 4500 K (Babánková et al. 2006b) are very close to the low-temperature component in meteor spectra that exhibits 3800–6000 K independent of the mass of the impacting body or its velocity (specifically in the ranges of 35 and 72 km s⁻¹ and masses between 1025 g and 1 g, according to Jenniskens et al. 2004). A spectroscopic survey of high-power terawatt-class laser plasma interaction with samples of meteorites has not been explored so far. Several studies that focused on the simulation of high-density energy events connected with asteroid or meteoroid bodies have been published.

Zakharov (2003) concluded that among other phenomena such as barium releases from the Earth’s magnetosphere, collisionless deceleration of supernova remnants or related shock-wave generation in the interstellar medium, near-Earth anti-asteroid explosions could be also reproduced in the laboratory using laser experiments. Milley et al. (2007) simulated meteor luminosity through laser ablation of meteorites. The first comprehensive work proposing that laboratory-based laser ablation techniques can be used not only to study the size of the luminous region, but also to predict spectral features, estimate the luminous efficiency factor, and assess the role of chemically differentiated thermal ablation of meteoroids was published by Hawkes et al. (2007). Ebert et al. (2017) simulated the virtually instantaneous melting of target rocks during meteorite impacts. They discovered that the entropy changes for laser-melting of a sandstone and an iron meteorite correspond to a minimum impact velocity of 6 km s⁻¹, inducing peak shock pressures of 100 GPa in the target.

Alongside with these studies, the simulation of space weathering together with the deflection of asteroids by lasers remains the most frequently studied research topic connected with application of lasers in this field (Park & Mazanek 2003). Recently, Aristova et al. (2018) studied impact physics of nuclear explosion on hazardous asteroids, Moroz et al. (1996) simulated using laser ablation optical effects of impact melting and repeated crystallization on asteroidal surfaces, and Kurahashi et al. (2002) conducted laser ablation laboratory simulation of space weathering focused on finding the source of the difference between reflectance spectra of ordinary chondrites and their parent bodies, i.e., S-type asteroids. Loeffler et al. (2008) studied the effect of the redeposition of impact-ejecta on mineral surfaces using laser ablation.

To facilitate the understanding of meteor spectra and in order to increase the precision of the qualitatively assigned emission, we employed a high-power terawatt-class laser that can generate in one shot large volumes of plasma under strictly defined conditions. Alongside with the more than 1000× higher power in comparison with classical laboratory lasers, our terawatt-class laser-induced breakdown spectroscopy (TC-LIBS) also provides a great advantage in evaporation of a significantly larger area of the meteorite specimen. This occurs in a manner entirely to that induced by the plasma that is generated during meteoroid descent. Spectra have been recorded in situ by modern high-resolution echelle spectrograph alongside with a low-resolution astronomical meteor spectrograph that was used for the observation of real meteors. The current study provides a catalog of emission lines that we recorded in our experiments and highlights how low-resolution data can be interpreted.

2. Experimental details

Samples of chondrite meteorites (see Table 1) were ablated by sub-nanosecond laser pulses (pulse duration 300 ps, wavelength 1.315 μm) with an energy of 600 J generated by the high-power TW-class facility Prague Asterix Laser System (PALS; Jungwirth et al. 2001). The intensity of the laser radiation focused on the surface of a meteorite specimen reached 2.2 TW cm⁻². The experimental setup is depicted in Fig. 1. TC-LIBS spectra were simultaneously recorded by a high-resolution echelle spectrograph and the astronomical meteor spectrograph that was employed in spectroscopic surveys of meteors in direct observation. The instrumental equipment and methods are described in the following two subsections. The TC-LIBS spectra of these chondritic meteorites were then averaged in order to obtain the appropriate signal-to-noise ratio and

Table 1. Elemental composition of the meteorites used to calculate the synthetic spectra.

Type	Specification	Mg	Fe	Si	Ca	Cr	Mn	Ni	Na	Reference
CK5	NWA 8214	1	0.704	0.89	0.119	0.011	0.009	0.017	0.056	This work
CM2	DHO 1994	1	0.693	0.917	0.197	0.011	0.009	0.038	0.037	This work
CV3	NWA 3118	1	0.918	1.017	0.073	0.015	0.009	0.027	0.027	This work
CO3	JAH 815	1	0.718	0.939	0.094	0.013	0	0.042	0.045	This work
H3	SAU 567	1	0.65	0.975	0.053	0.009	0.008	0.036	0.082	This work
L3	RAS 445	1	0.608	0.991	0.071	0.013	0.009	0.048	0.067	This work
L3	SAU 571	1	0.682	1.054	0.07	0.011	0.009	0.033	0.092	This work
H	NWA 8212	1	0.408	1.104	0.052	0.012	0.009	0.014	0.065	This work
Av. spec.		1	0.673	0.986	0.091	0.012	0.008	0.032	0.059	This work
L		1	0.628	1.075	0.053	0.012	0.008	0.033	0.05	Drouard et al. (2018)
LL		1	0.547	1.082	0.056	0.013	0.006	0.024	0.051	Drouard et al. (2018)
H		1	0.855	1.045	0.054	0.012	0.007	0.047	0.048	Drouard et al. (2018)
CM		1	0.753	0.967	0.066	0.012	0.006	0.042	0.027	Drouard et al. (2018)
HED		1	1.5	4.796	1.086	0.025	0.046		0.076	Drouard et al. (2018)
	PER2015	1	1	3	0.52	0.001	0.086	0.02	0.02	Ferus et al. (2018b)
	PER1	1	0.778	0.926	0.036	0.009	0.002		0.074	Trigo-Rodriguez et al. (2004a)
	PER2	1	0.807	1.136	0.02	0.009	0.003		0.08	Trigo-Rodriguez et al. (2004a)
	PER3	1	1.024	1.176	0.032	0.011	0.009		0.094	Trigo-Rodriguez et al. (2004a)
	PER4	1	1.01	1.031	0.062	0.011	0.006	0.015	0.113	Trigo-Rodriguez et al. (2004a)
	PER5	1	1.048	1.205	0.025	0.01	0.005	0.041	0.084	Trigo-Rodriguez et al. (2004a)
	LEO	1	1	1.3	0.12	0.001	0.081	0.02	0.01	Ferus et al. (2018b)
	LEO	1	1.025	1.266	0.033	0.005	0.009		0.101	Trigo-Rodriguez et al. (2004a)
	AND	1		1.176	0.015	0.009	0.01	0.019	0.094	Trigo-Rodriguez et al. (2004a)
	SPO2	1		2.564	0.028	0.028	0.018	0	0.282	Trigo-Rodriguez et al. (2004a)
	SPO1	1	0.879	1.099	0.026	0.009	0.006	0.016	0.11	Trigo-Rodriguez et al. (2004a)
	SPO3	1		1.124	0.027	0.007	0.007	0.026	0.09	Trigo-Rodriguez et al. (2004a)
	SPO3r	1		0.947	0.034	0.006	0.007	0.02	0.076	Trigo-Rodriguez et al. (2004a)
	SPO4	1	1.492	1.639	0.061	0.01	0.009	0.041	0.148	Trigo-Rodriguez et al. (2004a)
	Geminid 200111	1	1	1.16	0.04		0.008	0.08	0.03	Madieto et al. (2013b)
	Geminid 151209	1	0.909	1.055	0.027		0.007	0.027	0.055	Madieto et al. (2013a)
	GEMr	1	1.111	1.289	0.020		0.005		0.133	Trigo-Rodriguez et al. (2004b)

the qualitative average analysis that is representative for a spectrum of a chondrite meteorite. These data qualitatively provide spectral features that are expected in the emission from the meteor plasma. These spectra and their recorded dominant features were compared with the average synthetic spectrum calculated for a wide range of temperatures and averaged for the chemical composition of a chondrite in Table 1. Elemental composition of the particular chondrite meteorite studied in this work by TC-LIBS was examined using an energy dispersive analysis (EDS). The physical constants for this calculation were taken from the NIST (National Institute of Standards and Technology) database. We would like to highlight that the intention of this work is in the first place to provide a qualitative catalog of spectral features, their experimental measurement, and their comparison with synthetic spectra. A quantitative comparison of spectra recorded for a particular specimen that is ablated by high-power TW-class laser, but also by a standard laboratory Nd:YAG laser, an excimer laser and a femtosecond Ti:Sapphire TW-laser will be provided in a follow-up study.

2.1. Simulation of meteor plasma using the PALS laser facility

The plasma creation and radiation during the meteoroid descent in the atmosphere was simulated using the high-power laser PALS. The laser beam was focused by a plano-convex lens ($f/2$, $f = 60$ cm) on the target, which was positioned out of focus; the spot size was 1 cm in diameter. All the experiments were performed under pressure of 2 mbar, corresponding to the

altitudes that are typical for the very early stages of ablation of the meteoroid body ablation (above 110 km).

2.2. Optical emission spectroscopy of laser-induced breakdown plasma

Complex spectra within the entire UV/VIS range have been recorded by the High Resolution Echelle Spectra Analyzer ESA 4000 (LLA Instruments GmbH, Germany). The optical analyzer unit enables a spatially and temporally resolved image at the lowest spectral intensities. The resolution ranges from a few pm in the range 200–780 nm with resolution of 0.005 nm (200 nm) to 0.019 nm (780 nm). Simultaneously, the spectra were recorded for direct calibration by our astronomical meteor spectrograph that is directly employed in the observation of real meteors for comparative measurements. The spectrograph is based on the high-resolution camera PointGrey Grasshopper3 GS3-U3-32S4M-C with high quantum efficiency ($QE = 76\%$, 525 nm), dynamical range (71.34 dB), with CMOS chip Sony Pregius 2048 × 1536 px, and a grating of 1000 lines mm^{-1} , which allows a resolution of 0.48 nm px^{-1} . The spectral intensity recorded by the instrument is calibrated using standard sources, such as a deuterium lamp, a tungsten source and calibration using standard spectra of Venus. Wavelength calibration is achieved using high-resolution data and standard wavelengths of calibration sources (deuterium lamp). In our measurements, for every meteorite sample, the echelle spectrograph was set to trigger 1 μs after the laser pulse with the gate open for 4 μs for a total accumulation of one signal after one large laser shot. The PALS high-power

Fig. 1. Panel A: vacuum interaction chamber with ablation set-up. A photograph of a spectrum is shown in the embedded picture (left). Panel B: detailed experimental set-up with a collimator of Echelle spectrograph. Panel C: low resolution astronomical camera for comparative measurement. Panel D: sample of a meteorite prepared for the TC-LIBS experiment (left), high-power laser induced dielectric breakdown inside the interaction chamber (right).

laser provides a single 600 J-laser shot every 30 min. The low-resolution astronomical meteor spectrograph opened the gate for 1 s after it was triggered by the laser system.

2.3. Bulk elemental analysis of chondrite samples

Chemical analyses of meteorites were provided by secondary and backscatter electron imaging (SEI/BSE) conducted with the

JEOL JSM-6380 LV SEM system at the National Technical University of Athens, Greece. This system is equipped with the Energy Dispersive X-Ray Analysis (EDX) from Oxford Instruments, and it is controlled by the INCA software. Prior to any quantitative chemical analyses the instrument was calibrated using a set of mineral standards. Analyses were performed in high vacuum, with an electron beam size of about $1\ \mu\text{m}$ and accelerating voltage of 20 kV. The beam current was generally set between 1–2 nA, and the analytical integration time was 120 s. The bulk analysis was performed by acquiring an X-ray spectrum while scanning and averaging an area of $100\ \text{mm}^2$.

3. Calculating the synthetic spectra

The measured high-resolution emission spectra were compared with the synthetic spectra calculated from high-precision data obtained from the NIST atomic spectral database (Kramida et al. 2018). This approach greatly facilitates the orientation in the experimental data because the user can visually quickly compare the measured spectra with the standard spectra from the database; in addition to this advantage, the positions of the simulated peaks can be also used as standard values for the wavelength calibration of the observed spectra. This subsection describes how the synthetic spectra were obtained.

The synthetic spectra were generated as a sum of the individual peaks corresponding to the energy transitions that are included in the simulation. The intensity of each peak was calculated according to the equation

$$I_{ul} = \frac{hc}{4\pi\lambda_{ul}} A_{ul} g_u N_i \frac{e^{-E_u/kT}}{Q(T)_i} \quad (1)$$

where I_{ul} , h , c , λ_{ul} , A_{ul} , g_u , N_i , E_u , k , T , and $Q(T)_i$ are the emission intensity, Planck's constant, the speed of light in vacuum, the transition wavelength, the Einstein A-coefficient of the transition, the g-factor of the upper energy level, the number of the particles in ionization state i , the energy of the upper level, the Boltzmann constant, temperature, and the partition function of the ionization state, respectively. The simulation assumed a local thermodynamic equilibrium and optically thin conditions where no self-absorption effects are present. The N_i value was calculated as the product of the abundance of the specific element and the relative abundance of the ionization states produced by ionization of the neutral atoms of the element. The relative concentrations of the ionization states were calculated according to the Saha equation. Synthetic spectra were calculated based on elemental abundances measured in our laboratory for several samples of chondritic meteorites by means of energy dispersive analysis (EDS). These specimens were also used for ablation by the PALS laser. The average elemental composition is shown in the Table 1 and compared with values from the current literature.

The values of the electron density were set to $1 \times 10^{14}\ \text{cm}^{-3}$, which is a typical value for the meteoric plasma (Borovička 1994). The synthetic spectra are provided in three different temperatures: 4000 K, which is typical for the lower temperature component of the meteoric spectra, 7000 K, which is often observed in our ablation experiments, and 10 000 K, which is near the value estimated for the so-called higher temperature component of the meteoric spectra (Borovička 1994). The maximum ionization degree of the species considered in this simulations was 1 (e.g., Ca II). Because the spectral resolution of most of the observation cameras used today is still lower than $1\ \text{nm}\ \text{px}^{-1}$, the observed spectral peak profiles are still strongly

influenced by the instrumental function of these spectrometers. For this reason, the simplest possible (Gaussian) peak profile was chosen as the profile function. The FWHM of the peaks was set to the same value as the spectral resolution of our observation camera used in this experiment (0.48 nm px^{-1}).

4. Results and discussion

4.1. Compilation of the spectral features

Although the meteoric spectra show considerable variability, certain groups of commonly observed spectra can be identified. The spectral features in this work are presented in the form of groups of spectral lines that occur in narrow spectral regions between approximately 370 and 660 nm.

The purpose of this data compilation is to provide a detailed description of the selected spectral features in terms of assignment to the energy transitions that contribute significantly to the appearance of the most frequently observed spectral lines in the meteor spectra. As candidates for the most prominent meteoric spectral features, the lines listed in the literature (Vojáček et al. 2015; Cepelcha 1971, 1966; IMC 2015¹) were selected. For an overview of all the selected spectral features, see Fig. 2, where our laboratory low-resolution spectrum acquired with the observation camera is compared to the real spectra of several meteors (Ferus et al. 2018a).

Because this study uses extensively the experimental data measured by the TC-LIBS of real meteoritic samples, we mainly focussed on the spectral lines assigned to the metallic species. The spectral lines of atmospheric gases that are also observed in meteoric spectra are included, but they are not paid much attention.

All the spectral features are listed in the Table A.1. Each feature is composed of one or more spectral lines that can include several energy transitions. The features are separated by horizontal lines that reach over all the table columns. Each feature is labeled by a tag (F1, F2, etc.) that serves as its reference in the text and figures. Each feature in the table is accompanied by a figure (Figs. B.1–B.4). All the marked peaks (their positions and heights) are listed in the corresponding part the Table A.1. In addition to the experimental and simulated spectra, the individual energy transitions are plotted (as a stick diagram). The columns of Table A.1 can be divided into two main groups. The first group contains the data of the energy transitions, and the second group collects the information about the selected spectral lines (peaks). Each spectral line can be composed of several energy transitions. The table lines (transitions) contributing to a specific peak are separated by one column spanning horizontal lines in the last four columns of the table (peak wavelengths and intensities). Each peak begins at the row of the table where the values of its wavelength and height are written and ends at the nearest following horizontal line. The beginning and end of each peak were determined by the nearest left and nearest right local minima, respectively. Lines that can be observed too far from the listed transitions are not included in the table, nor are they marked in the figures.

Only transitions with known Einstein A-coefficients were added into the table. Moreover to simplify the present table we included only the energy transitions gathered from the NIST Atomic Spectral Database Kramida et al. (2018) whose intensities (calculated using the Eq. (1)) are higher than 10% of the

maximum calculated intensity within the particular spectral feature. Similarly, only the peaks exceeding the height of 10% of the highest peak in the feature are selected.

4.2. Description of spectral features

This section contains a brief description of the selected spectral features. Only interesting or doubtful cases are listed.

- F1 (371.58–375.35 nm): almost only lines of Fe I.
- F2 (381.64–389.03 nm): the low-temperature lines of Mg I and Fe I, which partially overlap. The lines of Si II can also become important at higher temperatures.
- F3 (392.95–397.19 nm): typical for fast meteors. The most significant lines belong to the Ca II doublet. These lines are overlapped by two Al I lines of comparable intensity, however. This may cause difficulties when the lines are used for the quantitative analysis.
- F4 (402.69–406.74 nm): the low-temperature lines of Fe I and Mn I.
- F5 (412.68–413.50 nm): the fast meteor feature, the Si II line (higher temperatures), is very close to a line of Fe I, which is much more intensive at lower temperatures, however.
- F6 (419.67–432.97 nm): low-temperature lines of Fe I, Ca I, and Cr I.
- F7 (437.18–440.89 nm): low-temperature and weak lines of Fe I; at higher temperatures, lines of Mg II and Fe II can appear.
- F8 (441.65–448.44 nm): fast meteors, contains the low-temperature lines of Ca I and Fe I, at higher temperatures, lines of Mg II can appear. The measured high-resolution spectrum also contains one significant peak that can be assigned to Mn I energy transitions.
- F9 (451.61–454.40 nm): low-temperature lines of Ca I and Fe I. At high temperature, the lines of Fe II become more significant. The measured high-resolution spectrum also contains one significant peak that was not selected and included in the table because the Einstein A-coefficient of the nearby Fe I transition is missing.
- F10 (469.90–470.70 nm): low-temperature lines of Mg I.
- F11 (486.80–496.16 nm): low-temperature lines of Fe I. At high temperature, the line of Fe II becomes more significant.
- F12 (500.74–502.11 nm): fast meteors, Fe I and Fe II lines, together with transitions of Ti I, can also contribute to the lines observed in this spectral region.
- F13 (510.59–511.49 nm): contains Fe I and Fe II transitions.
- F14 (516.33–522.41 nm): low-temperature and weak lines of Mg I, Fe I, and Cr I.
- F15 (526.49–527.34 nm): low-temperature Fe I lines, lines of Ca I are also of comparable intensity in this spectral region.
- F16 (532.60–533.60 nm): lines of atmospheric O I (at higher temperatures) and Fe I (lower temperatures).
- F17 (536.75–545.96 nm): in this spectral region and at low temperature Fe I, Cr I lines are most significant. At high temperature, the lines of Fe II become more significant.
- F18 (552.10–553.40 nm): the dominant Mg I line.
- F19 (557.29–561.94 nm): the dominant lines in this spectral region belong to Ca I and Fe I. At high temperature, the lines of Fe II can appear.
- F20 (588.60–589.98 nm): low-temperature Na I lines (usually a very intensive feature).
- F21 (623.10–624.42 nm): low-temperature lines of Fe I. At high temperature, the lines of Fe II and Si II can appear.

¹ International Meteor Conference (IMC) 2015 (Mistelbach, Austria, August 27) (IMO), 16–23.

Fig. 2. *Panel A:* high-resolution (gray) together with the low-resolution (red) spectrum. The most significant spectral lines are labeled. *Panel B:* examples of spectra recorded by observational spectrographs. Starting with the upper spectrum of Perseid 20150811_014658 (brown), Sporadic 20161227_020734 (red), Perseid 20150812_231001 (black), Leonide 20161117_042009 (blue), Ursae Majorid 20161213_014212 (green), Alpha Camelopardalid 20161002_013415 (purple), and Perseid 20150812_232102 (wine). Overview of the selected spectral features (marked with gray lines). The detailed description of the individual spectral lines is provided in Table A.1.

- F22 (634.32–637.52 nm): fast meteors, high-temperature lines of Si II.
- F23 (645.24–649.88 nm): lines of atmospheric O I and N I, but the lines of Ca I and Fe I are also present in this region.
- F24 (655.88–656.69 nm): fast meteors, H I lines. At the experimental spectrum only the left wing of the spectral line can be seen.
- F25 (674.55–679.41 nm): low-temperature lines of Fe I and Ni I. At higher temperature, the lines of Mg II and N I can appear.
- F26 (693.72–698.59 nm): in this spectral region and at low temperature Fe I, Cr I lines are most significant. At high temperature, the lines of Fe II and N I become more significant.

4.3. Meteor spectra in the laboratory: advantages, challenges, and limitations

Evaluating meteor emission spectra is a very complex scientific problem. Our experimental spectra depicted in panel A of Fig. 2, as well as several examples of spectra recorded by observational spectrographs in panel B, exhibit a series of overlapping bands that are typical for complex multicomponent matrices. Our experimental data as well as their comparison with synthetic spectra calculated using the NIST database show that position, range, and intensity of many spectral features can depend not only on the chemical composition of the meteoroid body, but also on their overlapping and on the temperature of the plasma. Meteor spectra recorded by the low-resolution observational camera were obtained by the analysis of a spectrum photogra-

phy. For this analysis, theoretical tables cannot serve as calibration spectroscopic standard. Experimental LIBS of chondrites by terawatt-class laser and their assignment introduced in this study can therefore help with the precise assignment of spectral lines. In Table A.1 we show that wavelengths assigned to features observed in meteor spectra can differ. Experimental data can provide a standard for the spectral assignment for such complicated and complex matrices. Experimental data also show that considering intensity and number of spectral features in UV region between 115–400 nm, accuracy and sensitivity of meteor spectroscopy could be improved by measuring in this range. However, this is beyond the capabilities of the current instrumentation; detection outside Earth's atmosphere using very high-resolution spectrographs are required. Standard observational cameras operate in the 400 nm to 780 nm region, and emission lines above 300 nm are significantly attenuated by absorption in atmospheres as well as by the decreasing sensitivity of detectors. On the other hand in regions of longer wavelengths we performed in our laboratory systematic studies of the Rydberg states of atoms in the near- and mid-infrared ranges (NIR and MIR) (Civiš et al. 2011, 2012a,b,c,d, 2013a,b) (e.g., Fourier transform type) (Kawaguchi et al. 2008; Civiš et al. 2012e,c,f). Molecules and atomic species exhibit strong emission spectra under these conditions. In this manner, the elemental and molecular compositions of the objects can be simultaneously studied in the NIR and MIR regions. However, there are several limitations: the emission spectra of atoms are either not known or they are not assigned to Rydberg states that emit infrared radiation.

We supply a comparison of averaged spectra recorded by TC-LIBS of chondrite specimens with a selection of several spectra of meteors recorded at the Observatory Valašské Meziříčí (Czech Republic, Moravia - Zlín Region, GPS 49.46373, 17.97366). Our TC-LIBS measurements exhibit a wide range of emission lines. The most intense include Fe I, II, Mg I, II, Ca I, II, Mn I, Si II, Cr I, II, Ti I, Al I, Na I, H I, and N I, II (as described in Sect. 4.2, Figs. 2 and B.1–B.5, and Table A.1). However, we should note that several studies reported a number of rather extraordinary spectra: For instance, our experiments always exhibit intense sodium lines. Meteors with expected chondrite composition exhibit either a lack of sodium (Borovička et al. 2005) or a high concentration of sodium is described (Trigo-Rodríguez & Llorca 2007). The effect is explained by the depletion in Na through the exposure to solar radiation. Other meteors are classified based on the spectra by iron (in agreement with common meteorite classification). They are classified into mainstream and normal (with expected composition close to chondritic), and Fe poor (Vojáček et al. 2015). The TC-LIBS experiments will also facilitate a more precise classification, when the results are also connected with an abundance determination of particular elements. In these investigations, the simulation of relatively optically thin plasma around the path of the meteor is another challenging experimental problem.

Laboratory studies focused on meteor plasma are complicated by the fundamental problem connected with every experimental work: achieving experimental conditions as close to the real system as possible. The large volume of plasma produced by a terawatt-class laser exhibits a temperature of 9600 K and expands to 6 km s^{-1} (based on the Doppler shift of the spectral lines). Furthermore, regarding the high-energy output of 600 J of a terawatt-laser, this device is powerful enough to ablate significantly large areas of about 1 cm^2 of meteorite. This is similarly to the ablation of small meteoroid bodies in the atmosphere. This

is not possible with common laboratory lasers. These conditions can serve as a kind of simulation of the frontal shock wave region of the meteor.

This frontal shockwave contributes to the high-temperature component in meteor emission spectra. Two meteor spectral components were described by Borovička et al. for the first time in 1993 (Borovička 1994; Borovička & Betlem 1997; Borovička et al. 1999; Berezhnoy & Borovička 2010). The intense low-temperature component exhibits an excitation temperature ranging from 2900 K (lower extreme) to 6200 K (higher extreme) with a typical value of about 4500 K. Jenniskens et al. (2004) discovered a slight increase in the temperature with decreasing meteor altitude, but otherwise nearly constant values for meteoroids with speeds between 35 and 72 km s^{-1} and masses between 1025 g and 1 g. However, Ceplecha (1965) observed a decrease in the excitation temperature as a function of meteor luminosity and also reported a temperature of atomic oxygen lines in airglow plasma of about 14 000 K. Typical lines of the second component make up only 0.02% of the meteor vapor envelope in slow meteors, but account for more than 5% in fast meteors (Borovička 1994). These lines consist of high excitation of H I, Mg II, Si II, or Ca II that is also observed in the spectra of TC-LIBS recorded in this work. However, they are also mixed with a series of neutral lines in our case. We should note that global spectroscopic observations still oversimplify the much more complicated structure as well as temperature distribution in the plasma fireball that surrounds the meteoroid. The problem is described in detail in a recent comprehensive review by Silber et al. (2018). Our pilot study of TC-LIBS again opens this topic. TC-LIBS will certainly offer a unique opportunity to study the complicated phenomenon of meteoroid surface ablation under strictly controlled laboratory conditions on the macroscopic scale of large laser sparks.

5. Conclusions

We presented a compilation of the dominant spectral features of the plasma produced by ablation of chondrite meteoroids. Laboratory simulations of meteor plasma were performed by ablating of several specimens of chondrite meteorites by the high-power terawatt-class laser facility PALS. They reached the energy of 600 J and an output intensity of 2.2 TW cm^{-2} when focused on an area of 1 cm^2 of the meteorite specimen. The produced ablation plasma attained the temperature of 9600 K and plasma expanded with a velocity of 6 km s^{-1} . Spectra were recorded by the high-resolution echelle spectrograph, and for comparison and calibration, spectra were also recorded by the astronomical meteor spectrograph. All the spectral features were interpreted by synthetic spectra that were calculated based on the data from the NIST atomic spectra database. In this manner, we provide a data set for the evaluation of observational spectra that are recorded by the meteor spectrographs. Experimental spectra were also compared with selected meteor spectra.

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paper, LP, LL, JK, AK, AP, JH, TK, SC participated in the experiments, AK evaluated the data and wrote the paper, HS wrote the paper, LJ, RD contributed from the side of the PALS facility, EC conducted EDS and wrote the paper, MK supervised and conducted experiments in the PALS facility and wrote the paper.

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Appendix A: Energy transitions and lines of the spectral features

Table A.1. Spectral features of the meteors.

Label	Specie	Energy transitions				Peaks (experiment)				Peaks (simulation)					
		Lower energy level		Upper energy level		4000 K		High resolution		4000 K		7000 K		10 000 K	
		El. conf.	Term	J	El. conf.	Term	J	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}
F1	Fe I	3d ⁶ 4s ²	a ⁵ D	4	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ P°	5	371.99	1.3e-17	372.00	2.5e-01	372.01	2.6e-17		
	Fe I	3d ⁶ 4s ²	a ³ D	2	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ P°	2	372.26	1.4e-18	372.24	7.4e-02				
	Fe I	3d ⁷ (⁴ F) 4s	a ⁵ F	5	3d ⁷ (⁴ F) 4p	y ⁵ P°	2	373.49	6.1e-18	373.49	2.4e-01	373.62	2.4e-17	373.68	1.8e-17
	Ca II	3p ⁶ 4p	2P°	3/2	3p ⁶ 5s	2S	1/2	373.69	3.7e-21	373.71	1.9e-01				
	Fe I	3d ⁶ 4s ²	a ⁵ D	3	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ P°	4	373.71	8.2e-18						
	Fe I	3d ⁶ 4s ²	a ³ D	2	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ P°	3	374.56	4.8e-18						
	Fe I	3d ⁶ 4s ²	a ⁵ D	1	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ P°	2	374.83	2.6e-18	374.83	8.2e-02				
	Fe II	3d ⁶ (¹ D2) 4s	c ² D	5/2	3d ⁶ (³ P2) 4p	z ² P°	3/2	374.85	1.5e-26						
	Fe I	3d ⁷ (⁴ F) 4s	a ⁵ F	4	3d ⁷ (⁴ F) 4p	y ⁵ P°	4	374.95	3.7e-18	374.95	1.9e-01				
	F2	Fe I	3d ⁷ (⁴ F) 4s	a ⁵ F	5	3d ⁷ (⁴ F) 4p	y ⁵ D°	4	382.04	4.5e-18	382.04	1.8e-01	382.09	9.6e-18	382.06
Fe I	3d ⁶ 4s ²	a ⁵ D	4	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ D°	3	382.44	1.8e-18	382.45	5.8e-02	382.51	9.4e-18	383.22	2.5e-18	
Fe I	3d ⁷ (⁴ F) 4s	a ⁵ F	4	3d ⁷ (⁴ F) 4p	y ⁵ D°	3	382.59	2.7e-18	382.59	1.4e-01					
Fe I	3d ⁷ (⁴ F) 4s	a ³ F	3	3d ⁷ (⁴ F) 4p	y ³ D°	2	382.78	5.3e-19	382.78	1.3e-01					
Mg I	3s 3p	3P°	0	3s 3d	3D	1	382.94	3.4e-19	382.93	1.3e-01					
Mg I	3s 3p	3P°	1	3s 3d	3D	1	383.23	2.5e-19	383.23	2.6e-01					
Mg I	3s 3p	3P°	1	3s 3d	3D	2	383.23	7.6e-19							
Fe I	3d ⁷ (⁴ F) 4s	a ⁵ F	3	3d ⁷ (⁴ F) 4p	y ⁵ D°	2	383.42	1.3e-18							
Mg I	3s 3p	3P°	2	3s 3d	3D	3	383.83	1.4e-18	383.83	3.4e-01	383.78	4.0e-18	383.83	3.3e-18	
Mg I	3s 3p	3P°	2	3s 3d	3D	2	383.83	2.5e-19							
Fe I	3d ⁷ (⁴ F) 4s	a ³ F	2	3d ⁷ (⁴ F) 4p	y ³ D°	1	384.10	3.6e-19	384.11	1.2e-01					
Si II	3s 3p ²	2D	3/2	3s ² 4p	2P°	3/2	385.37	1.2e-28			385.97	1.8e-17	385.96	8.6e-19	
Si II	3s 3p ²	2D	5/2	3s ² 4p	2P°	3/2	385.60	1.0e-27	385.64	4.5e-02					
Fe I	3d ⁶ 4s ²	a ⁵ D	3	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ D°	2	385.64	2.0e-18							
Fe I	3d ⁶ 4s ²	a ³ D	4	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ D°	4	385.99	8.6e-18							
Si II	3s 3p ²	2D	3/2	3s ² 4p	2P°	1/2	386.26	4.7e-28							
Fe I	3d ⁶ 4s ²	a ⁵ D	2	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ D°	1	387.86	1.5e-18	387.86	4.6e-02					
Fe I	3d ⁶ 4s ²	a ³ D	3	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ D°	3	388.63	3.3e-18	388.63	8.3e-02	388.63	6.5e-18			
F3	Ca II	3p ⁶ 4s	2S	1/2	3p ⁶ 4p	2P°	3/2	393.37	9.2e-17	393.37	2.3e-01	393.37	1.8e-16	393.37	2.1e-16
Ca II	3p ⁶ 4s	2S	1/2	3p ⁶ 4p	2P°	1/2	396.85	4.7e-17	396.85	3.4e-01	396.85	9.2e-17	396.85	3.3e-15	
F4	Mn I	3d ⁵ 4s ²	a ⁶ S	5/2	3d ⁵ (⁶ S) 4s 4p (³ P°)	z ⁶ P°	7/2	403.08	8.8e-19	403.09	2.5e-02	403.22	2.9e-18		
	Mn I	3d ⁵ 4s ²	a ⁶ S	5/2	3d ⁵ (⁶ S) 4s 4p (³ P°)	z ⁶ P°	5/2	403.31	6.4e-19	403.32	2.1e-02				
	Mn I	3d ⁵ 4s ²	a ⁶ S	5/2	3d ⁵ (⁶ S) 4s 4p (³ P°)	z ⁶ P°	3/2	403.45	4.1e-19	403.46	2.0e-02				
	Fe I	3d ⁷ (⁴ F) 4s	a ³ F	4	3d ⁷ (⁴ F) 4p	y ³ P°	4	404.58	1.5e-18	404.59	5.1e-02	404.58	3.0e-18	404.58	2.5e-20
	Cr II	3d ⁵	b ⁴ D	5/2	3d ⁴ (³ D) 4p	z ⁴ P°	3/2	405.41	2.7e-25					405.41	7.9e-21
	Fe I	3d ⁷ (⁴ F) 4s	a ³ F	3	3d ⁷ (⁴ F) 4p	y ³ P°	3	406.36	7.6e-19	406.37	4.5e-02	406.36	1.5e-18	406.36	3.8e-19
F5	Si II	3s ² 3d	2D	5/2	3s ² 4f	2P°	7/2	413.09	2.5e-30	413.09	2.0e-02	413.21	2.6e-19	413.19	7.6e-20
Fe I	3d ⁷ (⁴ F) 4s	a ³ F	2	3d ⁷ (⁴ F) 4p	y ³ P°	3	413.21	1.3e-19	413.21	5.4e-02					
F6	Fe I	3d ⁷ (² G) 4s	a ¹ G	4	3d ⁷ (² G) 4p	z ¹ H°	5	419.91	1.5e-20	419.91	2.8e-02				
	Fe I	3d ⁷ (⁴ F) 4s	a ³ F	4	3d ⁷ (⁴ F) 4p	z ³ G°	4	420.20	1.9e-19	420.21	3.1e-02				
	Ca I	3p ⁶ 4s ²	1S	0	3p ⁶ 4s 4p	1P°	1	422.67	7.4e-17	422.68	1.2e-01	422.67	1.4e-16	422.68	9.1e-19
	Fe I	3d ⁶ (⁵ D) 4s 4p (³ P°)	z ⁵ P°	5	3d ⁶ (⁵ D) 4s 4p (⁶ D) 4d	e ⁵ G	6	422.74	8.8e-21	422.74	3.2e-02				

Table A.1. continued.

Label	Specie	Energy transitions					Peaks (experiment)					Peaks (simulation)				
		Lower energy level		Upper energy level		Term	4000 K		High resolution		Term	4000 K		7000 K		Term
		El. conf.	J	El. conf.	J		λ (nm)	I_{em}	λ (nm)	I_{em}		λ (nm)	I_{em}	λ (nm)	I_{em}	
Fe II		$3d^6(^3P^o)2s$	$5/2$	$3d^6(^3D)4p$	$7/2$	z^4D^o	423.32	8.9e-24	423.36	1.5e-02		423.32	6.3e-19			10000 K
Fe I		$3d^6(^3D)4s4p(^3P^o)$	1	$3d^6(^3D)4s$	2	e^7D	423.36	1.4e-20								
Fe I		$3d^6(^3D)4s4p(^3P^o)$	4	$3d^6(^3D)4s(^6D)5s$	4	e^7D	423.59	3.1e-20	423.60	2.5e-02						
Fe I		$3d^6(^3D)4s4p(^3P^o)$	2	$3d^6(^3D)4s(^6D)5s$	3	e^7D	425.01	2.4e-20	425.02	2.5e-02						
Fe I		$3d^7(^4F)4s$	3	$3d^7(^4F)4p$	3	z^3G^o	425.08	1.6e-19	425.09	3.0e-02						
Cr I		$3d^5(^6S)4s$	3	$3d^5(^6S)4p$	4	z^7P^o	425.43	2.4e-18	425.43	2.0e-02						
Fe I		$3d^6(^3D)4s4p(^3P^o)$	5	$3d^6(^3D)4s(^6D)5s$	5	e^7D	426.05	8.9e-20	426.06	5.6e-02						
Fe I		$3d^6(^3D)4s4p(^3P^o)$	3	$3d^6(^3D)4s(^6D)5s$	4	e^7D	427.12	2.9e-20	427.12	2.9e-02						
Fe I		$3d^7(^4F)4s$	4	$3d^7(^4F)4p$	5	z^3G^o	427.18	7.4e-19	427.18	8.5e-02						
Fe II		$3d^6(^3P^o)2s$	$3/2$	$3d^6(^3D)4p$	$1/2$	z^4D^o	427.33	2.1e-25								
Cr I		$3d^5(^6S)4s$	3	$3d^5(^6S)4p$	3	z^7P^o	427.48	1.9e-18	427.49	2.0e-02						
Fe I		$3d^7(^4F)4s$	3	$3d^6(^3P^o)4s4p(^3P^o)$	2	z^5S^o	428.24	2.4e-20								
Cr I		$3d^5(^6S)4s$	3	$3d^5(^6S)4p$	2	z^7P^o	428.97	1.4e-18	428.97	1.6e-02						
Fe I		$3d^7(^4F)4s$	4	$3d^7(^4F)4p$	4	z^5G^o	429.41	8.6e-20								
Fe II		$3d^6(^3P^o)2s$	$3/2$	$3d^6(^3D)4p$	$5/2$	z^4F^o	429.66	5.1e-25								
Fe I		$3d^6(^3D)4s4p(^3P^o)$	4	$3d^6(^3D)4s(^6D)5s$	5	e^7D	429.92	2.9e-20	429.93	2.2e-02						
Ca I		$3p^64s4p$	2	$3p^64p^2$	3	z^3P	430.25	3.6e-19	430.22	3.7e-02						
Fe II		$3d^6(^3P^o)2s$	$3/2$	$3d^6(^3D)4p$	$3/2$	z^4D^o	430.32	1.1e-24								
Fe I		$3d^7(^4F)4s$	3	$3d^7(^4F)4p$	4	z^3G^o	430.79	7.7e-19	430.79	8.7e-02						
Fe I		$3d^7(^4F)4s$	2	$3d^7(^4F)4p$	3	z^3G^o	432.58	8.2e-19	432.58	1.1e-01						
F7	Fe I	$3d^7(^4F)4s$	4	$3d^7(^4F)4p$	5	z^5G^o	438.35	2.0e-18	438.36	1.1e-01						
Mg II		$2p^64p$	$1/2$	$2p^65d$	$3/2$	z^4D^o	438.46	3.9e-30								
Fe II		$3d^6(^3P^o)2s$	$1/2$	$3d^6(^3D)4p$	$1/2$	z^4D^o	438.54	1.0e-24								
Mg II		$2p^64p$	$3/2$	$2p^65d$	$5/2$	z^4D^o	439.06	7.0e-30								
Fe I		$3d^7(^4F)4s$	3	$3d^7(^4F)4p$	4	z^5G^o	440.47	7.4e-19	440.50	7.0e-02						
F8	Ca I	$3p^64s4p$	0	$3p^64s4d$	1	z^3D	442.54	1.0e-19	442.55	2.3e-02						
Fe I		$3d^64s^2$	3	$3d^6(^3D)4s4p(^3P^o)$	4	z^7F^o	442.73	7.5e-20	442.73	1.4e-02						
Ca I		$3p^64s4p$	1	$3p^64s4d$	2	z^3D	443.50	2.3e-19	443.49	3.5e-02						
Ca I		$3p^64s4p$	1	$3p^64s4d$	1	z^3D	443.57	7.0e-20	443.56	2.4e-02						
Fe I		$3d^7(^4F)4s$	2	$3d^6(^3D)4s4p(^1P^o)$	2	x^5D^o	444.23	9.3e-21	444.24	1.6e-02						
Ca I		$3p^64s4p$	2	$3p^64s4d$	3	z^3D	445.48	4.1e-19	445.47	4.6e-02						
Ca I		$3p^64s4p$	2	$3p^64s4d$	2	z^3D	445.59	6.7e-20	445.60	2.5e-02						
Fe I		$3d^7(^4F)4s$	3	$3d^6(^3D)4s4p(^1P^o)$	3	x^5D^o	445.91	9.5e-21	445.92	1.9e-02						
Fe I		$3d^64s^2$	2	$3d^6(^3D)4s4p(^3P^o)$	3	z^7F^o	446.17	4.8e-20								
Fe I		$3d^7(^4F)4s$	2	$3d^6(^3P^o)4s4p(^3P^o)$	3	x^3D^o	446.66	6.9e-21								
Fe II		$3d^6(^3F^o)2s$	$5/2$	$3d^6(^3D)4p$	$3/2$	z^4F^o	447.29	1.1e-25								
Fe I		$3d^7(^4F)4s$	1	$3d^6(^3P^o)4s4p(^3P^o)$	2	x^3D^o	447.60	4.0e-21								
Fe II		$3d^6(^3F^o)2s$	$5/2$	$3d^6(^3D)4p$	$3/2$	z^4F^o	448.11	3.9e-27	448.12	5.2e-02						
Mg II		$2p^63d$	$5/2$	$2p^64f$	$7/2$	z^3D^o	448.12	2.0e-28								
Mg II		$2p^63d$	$5/2$	$2p^64f$	$7/2$	z^3D^o	448.12	2.0e-28								
Mg II		$2p^63d$	$3/2$	$2p^64f$	$5/2$	z^3D^o	448.13	2.7e-27								

Table A.1. continued.

Label	Specie	Energy transitions				Peaks (experiment)				Peaks (simulation)			
		Lower energy level		Upper energy level		High resolution		4000 K		7000 K		10 000 K	
		El. conf.	Term	J	El. conf.	Term	J	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}
F9	Fe II	$3d^6(^3F_2)4s$	b^4F	$^9/2$	$3d^6(^5D)4p$	z^4F^o	$7/2$	452.02	1.0e-24	452.87	7.9e-20	452.23	3.2e-19
	Fe II	$3d^6(^3F_2)4s$	b^4F	$5/2$	$3d^6(^5D)4p$	z^4D^o	$3/2$	452.26	3.9e-24			452.23	1.7e-18
	Ca I	$3p^63d4s$	1D	2	$3p^64s\text{ np}$	w^1P^o	1	452.69	8.8e-21	452.72	1.2e-02		
	Fe I	$3d^7(^4P)4s$	a^3P	3	$3d^6(^5D)4s\ 4p(^1P^o)$	x^5D^o	4	452.86	3.0e-20	452.86	1.8e-02		
	Fe I	$3d^7(^4F)4s$	a^3F	4	$3d^7(^4F)4p$	y^5F^o	4	453.11	1.0e-20				
	Fe II	$3d^6(^3F_2)4s$	b^4F	$3/2$	$3d^6(^5D)4p$	z^4D^o	$3/2$	454.15	4.2e-25				
F10	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7D^o	2	$3d^8$	3P	1	470.10	8.4e-22	470.28	1.2e-20	470.30	3.9e-20
	Mg I	$3s3p$	$^1P^o$	1	$3s\ 5d$	1D	2	470.30	5.6e-21	470.31	2.4e-02		2.2e-21
F11	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	3	$3d^6(^5D)4s(^6D)5s$	e^7D	2	487.13	1.6e-20	487.14	2.9e-03	487.16	3.5e-20
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	1	$3d^6(^5D)4s(^6D)5s$	e^7D	1	487.21	9.6e-21	487.22	2.7e-03		
	Ca I	$3p^63d4s$	1D	2	$3p^64s\ 4f$	$^1F^o$	3	487.81	1.6e-20	487.83	2.2e-03	487.80	3.1e-20
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	2	$3d^6(^5D)4s(^6D)5s$	e^7D	2	489.08	1.5e-20	489.09	3.0e-03	489.12	6.0e-20
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	4	$3d^6(^5D)4s(^6D)5s$	e^7D	3	489.15	3.1e-20	489.16	5.0e-03		
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	3	$3d^6(^5D)4s(^6D)5s$	e^7D	3	491.90	1.8e-20	491.91	3.0e-03	492.39	1.8e-18
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	5	$3d^6(^5D)4s(^6D)5s$	e^7D	4	492.05	5.0e-20	492.07	6.8e-03		
	Fe II	$3d^54s^2$	a^6S	$5/2$	$3d^6(^5D)4p$	z^6P^o	$3/2$	492.39	3.1e-23	492.39	1.2e-19		
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	4	$3d^6(^5D)4s(^6D)5s$	e^7D	4	495.73	1.6e-20	495.78	8.0e-03		
	Fe I	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7F^o	6	$3d^6(^5D)4s(^6D)5s$	e^7D	5	495.76	8.1e-20	495.75	1.9e-19	495.75	1.2e-19
F12	Fe I	$3d^7(^4F)4s$	a^5F	5	$3d^6(^5D)4s\ 4p(^3P^o)$	z^5F^o	5	501.21	3.2e-20	501.22	7.7e-03	501.21	6.3e-20
	Fe II	$3d^54s^2$	a^6S	$5/2$	$3d^6(^5D)4p$	z^6P^o	$5/2$	501.84	2.4e-23	501.84	1.2e-02		
F13	Fe I	$3d^7(^2H)4s$	a^1H	5	$3d^7(^2G)4p$	z^1H^o	5	511.04	2.5e-22	511.03	1.2e+02	511.04	1.8e-21
	Fe I	$3d^64s^2$	a^5D	4	$3d^6(^5D)4s\ 4p(^3P^o)$	z^7D^o	4	511.04	3.2e-20			511.27	9.9e-21
	Fe II	$3d^6(^5D)4d$	6P	$5/2$	$3d^6(^5D)4f$	$^2[4]^o$	$7/2$	511.22	2.7e-32	511.21	2.2e+01		
	Fe II	$3d^6(^5D)4d$	6D	$5/2$	$3d^6(^5D)4f$	$^2[3]^o$	$5/2$	511.30	6.0e-32	511.30	3.4e+01		
F14	Mg I	$3s3p$	$^3P^o$	0	$3s\ 4s$	3S	1	516.73	3.6e-19	516.75	1.0e-01	517.26	2.1e-18
	Fe I	$3d^7(^4F)4s$	a^3F	4	$3d^6(^5D)4s\ 4p(^3P^o)$	z^3D^o	3	516.75	2.0e-19			516.91	4.4e-18
	Fe II	$3d^54s^2$	a^6S	$5/2$	$3d^6(^5D)4p$	z^6P^o	$7/2$	516.90	8.1e-23	516.90	4.3e-02		
	Mg I	$3s3p$	$^3P^o$	1	$3s\ 4s$	3S	1	517.27	1.1e-18	517.28	1.2e-01		
	Mg I	$3s3p$	$^3P^o$	2	$3s\ 4s$	3S	1	518.36	1.8e-18	518.36	1.6e-01	518.36	3.5e-18
	Cr I	$3d^5(^6S)4s$	a^5S	2	$3d^5(^6S)4p$	z^5P^o	1	520.45	3.3e-19	520.46	3.7e-02	520.70	2.4e-18
	Cr I	$3d^5(^6S)4s$	a^5S	2	$3d^5(^6S)4p$	z^5P^o	2	520.60	5.5e-19	520.61	4.2e-02		
	Cr I	$3d^5(^6S)4s$	a^5S	2	$3d^5(^6S)4p$	z^5P^o	3	520.84	7.6e-19	520.85	5.1e-02		
F15	Fe II	$3d^6(^5D)4d$	f^4D	$7/2$	$3d^6(^5D)4f$	$^2[2]^o$	$5/2$	526.84	1.8e-32	526.97	1.9e-18	526.98	1.0e-19
	Fe I	$3d^7(^4F)4s$	a^5F	5	$3d^6(^5D)4s\ 4p(^3P^o)$	z^5D^o	4	526.95	8.3e-19	526.96	8.8e-03		
	Fe II	$3d^6(^5D)4d$	e^6G	$7/2$	$3d^6(^5D)4f$	$^2[5]^o$	$9/2$	527.00	1.0e-31				
	Ca I	$3p^63d4s$	3D	3	$3p^63d\ 4p$	$^3P^o$	2	527.03	8.0e-20	527.04	3.7e-03		
	Fe I	$3d^7(^4F)4s$	a^3F	2	$3d^6(^5D)4s\ 4p(^3P^o)$	z^3D^o	1	527.04	9.1e-20				
	Fe II	$3d^6(^5D)4d$	e^6G	$7/2$	$3d^6(^5D)4f$	$^2[3]^o$	$7/2$	527.11	1.2e-32				
F16	Fe I	$3d^7(^4F)4s$	a^5F	4	$3d^6(^5D)4s\ 4p(^3P^o)$	z^5D^o	3	532.80	5.3e-19	532.81	5.5e-03	532.82	5.9e-20
	Fe I	$3d^7(^4F)4s$	a^3F	3	$3d^6(^5D)4s\ 4p(^3P^o)$	z^3D^o	3	532.85	3.4e-20			533.00	1.0e-19
	N I	$2s\ 2p^4$	$4P$	$5/2$	$2s^22p^3(^3P)4p$	$4D^o$	$7/2$	532.86	1.5e-29				
	O I	$2s^22p^3(^4S^o)3p$	$5P$	1	$2s^22p^3(^4S^o)5d$	$5D^o$	0	532.91	9.5e-30				
	O I	$2s^22p^3(^4S^o)3p$	$5P$	1	$2s^22p^3(^4S^o)5d$	$5D^o$	1	532.91	2.1e-29				

Table A.1. continued.

Label	Specie	Lower energy level			Upper energy level			Energy transitions			Peaks (experiment)			Peaks (simulation)		
		El. conf.	Term	<i>J</i>	El. conf.	Term	<i>J</i>	<i>J</i>	<i>J</i>	<i>J</i>	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}
F17	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	1	$2s^2 2p^3 ({}^4S^{\circ}) 5d$	${}^5D^{\circ}$	2	532.91	1.7e-29		537.02	1.1e-02	537.15	6.3e-19	537.10	4.3e-20
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	2	$2s^2 2p^3 ({}^4S^{\circ}) 5d$	${}^5D^{\circ}$	2	532.97	2.8e-29		537.17	2.7e-02	537.15	6.3e-19	537.10	4.3e-20
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	2	$2s^2 2p^3 ({}^4S^{\circ}) 5d$	${}^5D^{\circ}$	3	532.97	4.4e-29		537.58	4.2e-03	537.58	4.2e-03	537.58	4.2e-03
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	3	$2s^2 2p^3 ({}^4S^{\circ}) 5d$	${}^5D^{\circ}$	3	533.07	2.2e-29		538.35	7.4e-03	538.35	7.4e-03	538.34	2.3e-20
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	3	$2s^2 2p^3 ({}^4S^{\circ}) 5d$	${}^5D^{\circ}$	4	533.07	8.5e-29				539.71	3.2e-19	539.68	1.6e-20
	Fe I	$3d^7 ({}^4F) 4p$	z^5G°	4	$3d^7 ({}^4F) 4d$	e^5H	5	537.00	2.4e-21		537.02	1.1e-02	537.15	6.3e-19	537.10	4.3e-20
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	3	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	2	537.15	3.2e-19		537.17	2.7e-02	537.15	6.3e-19	537.10	4.3e-20
	Fe II	$3d^6 ({}^5D) 4d$	e^6G	$11/2$	$3d^6 ({}^5D_4) 4f$	$2[6]^{\circ}$	$11/2$	537.58	9.8e-32		537.58	4.2e-03	537.58	4.2e-03	537.58	4.2e-03
	Fe I	$3d^7 ({}^4F) 4p$	z^5G°	5	$3d^7 ({}^4F) 4d$	e^5H	6	538.34	3.7e-21		538.35	7.4e-03	538.34	2.3e-20	538.34	2.3e-20
	Fe II	$3d^6 ({}^5D) 4d$	e^4G	$11/2$	$3d^6 ({}^5D_3) 4f$	$2[6]^{\circ}$	$11/2$	538.71	5.4e-31				539.71	3.2e-19	539.55	4.2e-20
	Fe I	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	3	$3d^6 ({}^5D) 4s ({}^6D) 5s$	e^5D	4	539.32	3.6e-21				539.71	3.2e-19	539.68	1.6e-20
	Fe II	$3d^6 ({}^5D) 4d$	e^6G	$11/2$	$3d^6 ({}^5D_4) 4f$	$2[5]^{\circ}$	$11/2$	539.38	1.2e-31				540.61	4.0e-19	540.52	3.0e-20
	Fe II	$3d^6 ({}^5D) 4d$	$6S$	$5/2$	$3d^6 ({}^5D_0) 4f$	$2[3]^{\circ}$	$7/2$	539.59	2.6e-31		539.74	1.5e-02	540.61	4.0e-19	540.52	3.0e-20
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	4	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	4	539.71	1.6e-19				540.61	4.0e-19	540.52	3.0e-20
	Fe II	$3d^6 ({}^5D) 4d$	e^4G	$9/2$	$3d^6 ({}^5D_2) 4f$	$2[5]^{\circ}$	$11/2$	540.21	4.5e-31		540.44	9.8e-03	540.61	4.0e-19	540.52	3.0e-20
F18	Fe I	$3d^7 ({}^4F) 4p$	z^3G°	4	$3d^7 ({}^4F) 4d$	e^3H	5	540.42	2.0e-21		540.44	9.8e-03	540.61	4.0e-19	540.52	3.0e-20
	Fe II	$3d^6 ({}^5D) 4d$	f^4D	$1/2$	$3d^6 ({}^5D_2) 4f$	$2[1]^{\circ}$	$3/2$	540.51	5.7e-32				541.08	7.7e-03	541.38	4.8e-20
	Fe II	$3d^6 ({}^5D) 4d$	f^4D	$5/2$	$3d^6 ({}^5D_3) 4f$	$2[3]^{\circ}$	$5/2$	540.57	6.2e-32		540.58	1.6e-02	540.61	4.0e-19	540.52	3.0e-20
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	2	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	1	540.58	9.0e-20				541.08	7.7e-03	541.38	4.8e-20
	Cr I	$3d^4 4s^2$	a^5D	4	$3d^5 ({}^6S) 4p$	z^5P°	3	540.98	1.3e-21				541.12	9.3e-03		
	Fe I	$3d^7 ({}^4F) 4p$	z^3G°	3	$3d^7 ({}^4F) 4d$	e^3H	4	541.09	1.3e-21		541.08	7.7e-03	541.12	9.3e-03		
	Fe II	$3d^6 ({}^5D) 4d$	$6S$	$5/2$	$3d^6 ({}^5D_1) 4f$	$2[3]^{\circ}$	$7/2$	541.14	1.2e-31		541.12	9.3e-03	541.12	9.3e-03		
	Fe II	$3d^6 ({}^5D) 4s$	a^4G	$7/2$	$3d^6 ({}^5D) 4p$	z^4D°	$7/2$	541.41	9.0e-26				542.95	2.0e-20	542.83	8.5e-20
	Fe II	$3d^6 ({}^5D) 4d$	e^4G	$11/2$	$3d^6 ({}^5D_3) 4f$	$2[5]^{\circ}$	$11/2$	541.49	8.2e-32				542.95	2.0e-20	542.83	8.5e-20
	Cr II	$3d^4 (a^3P) 4s$	z^3G°	5	$3d^7 ({}^4F) 4d$	e^3H	6	541.52	3.0e-21				542.95	2.0e-20	542.83	8.5e-20
	Fe II	$3d^6 ({}^5D) 4s$	a^4P	$3/2$	$3d^4 ({}^5D) 4p$	z^4P°	$1/2$	542.09	2.8e-25				542.95	2.0e-20	542.83	8.5e-20
	Fe II	$3d^6 ({}^5D) 4s$	a^4G	$9/2$	$3d^6 ({}^5D) 4p$	z^4F°	$9/2$	542.52	1.2e-25				542.95	2.0e-20	542.83	8.5e-20
	Fe II	$3d^5 4s^2$	b^4G	$11/2$	$3d^6 ({}^3D) 4p$	w^4F°	$9/2$	542.78	2.8e-28				542.95	2.0e-20	542.83	8.5e-20
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	3	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	3	542.97	1.9e-19		542.98	2.9e-02	542.99	3.9e-19		
	Fe II	$3d^6 ({}^5D) 4d$	e^4G	$7/2$	$3d^6 ({}^5D_1) 4f$	$2[4]^{\circ}$	$9/2$	543.00	3.7e-31				542.99	3.9e-19		
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	1	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	0	543.45	9.4e-20		543.45	1.4e-02	543.45	1.4e-02	543.60	3.0e-20
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	1	$2s^2 2p^3 ({}^4S^{\circ}) 6s$	${}^5S^{\circ}$	2	543.52	1.5e-29							
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	2	$2s^2 2p^3 ({}^4S^{\circ}) 6s$	${}^5S^{\circ}$	2	543.58	2.5e-29							
	O I	$2s^2 2p^3 ({}^4S^{\circ}) 3p$	5P	3	$2s^2 2p^3 ({}^4S^{\circ}) 6s$	${}^5S^{\circ}$	2	543.69	3.5e-29							
	Fe II	$3d^6 ({}^5D) 4d$	f^4D	$3/2$	$3d^6 ({}^5D_3) 4f$	$2[1]^{\circ}$	$3/2$	544.24	7.9e-32				544.69	1.6e-20	544.48	2.9e-20
	Fe II	$3d^6 ({}^5D) 4d$	$6S$	$5/2$	$3d^6 ({}^5D_1) 4f$	$2[2]^{\circ}$	$5/2$	544.44	9.5e-32				544.69	1.6e-20	544.48	2.9e-20
	Fe II	$3d^6 ({}^5D) 4d$	f^4D	$3/2$	$3d^6 ({}^5D_3) 4f$	$2[2]^{\circ}$	$5/2$	544.58	1.3e-31				544.69	1.6e-20	544.48	2.9e-20
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	2	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	2	544.69	1.6e-19		544.70	2.2e-02				
	Fe II	$3d^6 ({}^5D) 4d$	e^4G	$5/2$	$3d^6 ({}^5D_0) 4f$	$2[3]^{\circ}$	$7/2$	545.01	1.1e-31							
	Fe I	$3d^7 ({}^4F) 4s$	a^5F	1	$3d^6 ({}^5D) 4s 4p ({}^3P^{\circ})$	z^5D°	1	545.56	1.0e-19		545.58	1.9e-02	545.56	2.0e-19	545.56	1.0e-20
	Fe II	$3d^6 ({}^5D) 4d$	e^6G	$9/2$	$3d^6 ({}^5D_4) 4f$	$2[5]^{\circ}$	$9/2$	545.59	6.2e-32							
F18	Fe II	$3d^6 ({}^3H) 4s$	b^2H	$9/2$	$3d^6 ({}^5D) 4p$	z^4D°	$7/2$	552.51	3.0e-26				552.84	1.8e-20	552.84	4.1e-20
	Mg I	$3s 3p$	$1P^{\circ}$	1	$3s 4d$	$1D$	2	552.84	9.4e-21		552.84	5.7e-03				
	Fe II	$3d^6 ({}^5D) 4d$	f^4D	$5/2$	$3d^6 ({}^5D_4) 4f$	$2[3]^{\circ}$	$5/2$	552.91	1.0e-31							

Table A.1. continued.

Label	Specie	Energy transitions				4000 K				Peaks (experiment)				Peaks (simulation)			
		Lower energy level		Upper energy level		4000 K		High resolution		4000 K		7000 K		10 000 K			
		El. conf.	Term	J	El. conf.	Term	J	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}	λ (nm)	I_{em}
Fe II	3d ⁵ 4s ²		b ⁴ G	9/2	3d ⁶ (³ D) 4p	w ⁴ F°	7/2	552.99	1.7e-28	552.98	2.1e-03						
Fe II	3d ⁶ (⁵ D) 4d		f ⁴ D	3/2	3d ⁶ (⁵ D ₄) 4f	2[1]°	1/2	553.03	3.9e-32								
N I	2s ² 2p ² (³ P) 3p		4D°	5/2	2s ² 2p ² (³ P) 5d	4F	5/2	557.59	2.1e-30								
Fe II	3d ⁶ (³ D) 4d		e ⁴ G	7/2	3d ⁶ (³ D ₃) 4f	2[3]°	7/2	557.79	1.2e-31								
Fe II	3d ⁶ (³ D) 4d		6S	5/2	3d ⁶ (³ D ₃) 4f	2[1]°	3/2	557.80	3.6e-32								
Fe II	3d ⁶ (³ D) 4d		4S	3/2	3d ⁶ (³ D ₂) 4f	2[2]°	3/2	557.99	4.4e-32								
Fe II	3d ⁶ (³ D) 4d		6S	5/2	3d ⁶ (³ D ₃) 4f	2[2]°	5/2	558.16	4.6e-32								
Ca I	3p ⁶ 3d 4s		3D	2	3p ⁶ 3d 4p	3D°	3	558.20	1.9e-20	558.21	1.9e-03						
Fe II	3d ⁶ (³ D) 4d		f ⁴ D	3/2	3d ⁶ (³ D ₄) 4f	2[3]°	5/2	558.39	2.7e-32								
Fe I	3d ⁶ (³ D) 4s 4p (³ P°)		z ⁵ F°	4	3d ⁶ (³ D) 4s (⁶ D) 5s	e ⁵ D	3	558.68	1.1e-20	558.69	1.6e-03						
Fe II	3d ⁵ 4s ²		b ⁴ G	5/2	3d ⁶ (³ D) 4p	w ⁴ F°	3/2	558.71	1.2e-28								
Fe II	3d ⁶ (³ D) 4d		e ⁴ G	7/2	3d ⁶ (³ D ₃) 4f	2[3]°	7/2	558.80	2.8e-32								
Fe II	3d ⁶ (³ D) 4d		e ⁴ G	7/2	3d ⁶ (³ D ₃) 4f	2[5]°	9/2	558.82	2.3e-31								
Ca I	3p ⁶ 3d 4s		3D	3	3p ⁶ 3d 4p	3D°	3	558.87	1.5e-19	558.89	8.1e-03						
Ca I	3p ⁶ 3d 4s		3D	1	3p ⁶ 3d 4p	3D°	2	559.01	1.9e-20	559.02	3.0e-03						
Ca I	3p ⁶ 3d 4s		3D	2	3p ⁶ 3d 4p	3D°	2	559.45	8.6e-20	559.47	5.1e-03	559.47	2.0e-19	559.47	1.1e-20		
Ca I	3p ⁶ 3d 4s		3D	1	3p ⁶ 3d 4p	3D°	1	559.85	5.9e-20	559.87	3.8e-03						
Ca I	3p ⁶ 3d 4s		3D	3	3p ⁶ 3d 4p	3D°	2	560.13	1.9e-20	560.15	2.0e-03						
Ca I	3p ⁶ 3d 4s		3D	2	3p ⁶ 3d 4p	3D°	1	560.28	1.9e-20	560.30	2.5e-03						
Fe I	3d ⁶ (³ D) 4s 4p (³ P°)		z ⁵ F°	1	3d ⁶ (³ D) 4s (⁶ D) 5s	e ⁵ D	1	560.29	1.8e-21								
Fe I	3d ⁶ (³ D) 4s 4p (³ P°)		z ⁵ F°	5	3d ⁶ (³ D) 4s (⁶ D) 5s	e ⁵ D	4	561.56	1.9e-20	561.58	1.8e-03	561.56	3.7e-20	561.56	3.0e-20	561.56	1.8e-21
Na I	2p ⁶ 3s		2S	1/2	2p ⁶ 3p	2P°	3/2	589.00	2.0e-17	589.01	4.7e-02	589.00	4.0e-17	589.00	4.2e-19	589.00	5.4e-20
Na I	2p ⁶ 3s		2S	1/2	2p ⁶ 3p	2P°	1/2	589.59	1.0e-17	589.61	3.1e-02	589.57	2.1e-17	589.57	2.1e-19	589.57	2.8e-20
Fe II	3d ⁶ (³ D) 4s		b ⁴ D	3/2	3d ⁶ (³ D) 4p	z ⁴ P°	3/2	623.84	1.2e-25	624.63	2.8e-21	623.84	1.2e-20	623.91	1.5e-19		
Si II	3s ² 4f		2F°	7/2	3s ² 6g	2G	9/2	623.96	9.7e-34								
Si II	3s ² 4f		2F°	5/2	3s ² 6g	2G	7/2	623.97	6.8e-34								
Fe I	3d ⁷ (⁴ P) 4s		a ⁵ P	1	3d ⁶ (³ D) 4s 4p (³ P°)	z ³ P°	2	624.06	3.9e-22								
Fe I	3d ⁶ (³ D) 4s 4p (³ P°)		z ⁵ P°	3	3d ⁶ (³ D) 4s (⁶ D) 5s	e ⁵ D	3	624.63	1.4e-21								
Fe II	3d ⁶ (³ D) 4s		b ⁴ D	5/2	3d ⁶ (³ D) 4p	z ⁴ P°	3/2	624.76	2.3e-25								
Si II	3s ² 4s		2S	1/2	3s ² 4p	2P°	3/2	634.71	8.4e-28	634.72	6.5e-03	634.71	2.4e-21	634.71	1.1e-19	634.71	1.1e-17
Fe I	3d ⁷ (⁴ P) 4s		b ³ P	1	3d ⁶ (³ D) 4p	y ³ D°	2	635.50	5.1e-22								
Fe I	3d ⁷ (⁴ F) 4s		a ⁵ F	5	3d ⁶ (³ D) 4s 4p (³ P°)	z ⁷ F°	6	635.87	1.1e-21								
Si II	3s ² 4s		2S	1/2	3s ² 4p	2P°	1/2	637.14	5.0e-28	637.14	2.9e-03						
O I	2s ² 2p ³ (⁴ S°) 3p		5P	2	2s ² 2p ³ (⁴ S°) 5s	5S°	2	645.44	1.3e-28								
O I	2s ² 2p ³ (⁴ S°) 3p		5P	3	2s ² 2p ³ (⁴ S°) 5s	5S°	2	645.60	1.8e-28								
Fe II	3d ⁶ (³ D) 4s		b ⁴ D	7/2	3d ⁶ (³ D) 4p	z ⁴ P°	3/2	645.64	4.2e-25								
Ca I	3p ⁶ 3d 4s		3D	2	3p ⁶ 3d 4p	3F°	3	646.26	3.1e-19	646.27	6.1e-03						
Fe I	3d ⁷ (⁴ F) 4s		a ⁵ F	4	3d ⁶ (³ D) 4s 4p (³ P°)	z ⁷ F°	5	646.27	1.9e-19								
Ca I	3p ⁶ 3d 4s		3D	3	3p ⁶ 3d 4p	3F°	3	647.17	3.8e-20	647.18	1.5e-03						
Fe II	3d ⁶ (³ F) 4s		c ⁴ F	9/2	3d ⁶ (³ G) 4p	x ⁴ G°	11/2	648.22	1.1e-27								
N I	2s ² 2p ² (³ P) 3p		4D°	7/2	2s ² 2p ² (³ P) 4d	4F	9/2	648.27	1.1e-28	649.39	4.5e-19						

Table A.1. continued.

Label	Specie	Energy transitions					Peaks (experiment)			Peaks (simulation)		
		Lower energy level		Upper energy level		Term	High resolution		4000 K	7000 K		10 000 K
		El. conf.	J	El. conf.	J		λ (nm)	I_{em}		λ (nm)	I_{em}	
F24	N I	$2s^2 2p^2 (^3P) 3p$	$3/2$	$2s^2 2p^2 (^3P) 4d$	$5/2$	$4F$	648.38	4.9e-29				
	N I	$2s^2 2p^2 (^3P) 3p$	$5/2$	$2s^2 2p^2 (^3P) 4d$	$7/2$	$4F$	648.48	7.3e-29				
	Ca I	$3p^6 3d 4s$	1	$3p^6 3d 4p$	2	$3F^\circ$	649.38	2.1e-19	649.39	3.6e-03	649.41	2.2e-20
	Fe I	$3d^6 4s^2$	6	$3d^7 (4F) 4p$	5	$z^5 G^\circ$	649.50	2.0e-20	649.50	1.5e-03		
	H I	2p	$1/2$	3d	$3/2$	2D	656.27	9.2e-27	656.25	1.6e-02	656.28	2.3e-19
	H I	2s	$1/2$	3p	$3/2$	2P $^\circ$	656.27	3.8e-27			656.28	2.8e-18
F25	H I	2s	$1/2$	3p	$1/2$	2P $^\circ$	656.28	1.9e-27				
	H I	2p	$3/2$	3d	$5/2$	2D	656.29	1.7e-26				
	H I	2p	$3/2$	3d	$3/2$	2D	656.29	1.8e-27				
	H I	2p	$3/2$	3d	$3/2$	2D	656.29	2.8e-27				
	Fe II	$3d^6 (^5D) 5p$	$5/2$	$3d^6 (^5D) 5d$	$7/2$	$4G$	675.00	9.6e-33	675.02	1.9e-21	675.14	6.1e-22
	Fe I	$3d^6 4s^2$	1	$3d^6 (^5D) 4s 4p (^3P^\circ)$	1	$z^3 P^\circ$	675.02	9.4e-22			675.10	6.9e-21
	Si II	$3s 3p (^3P^\circ) 4s$	$5/2$	$3s 3p (^3P^\circ) 4p$	$5/2$	$4D$	675.03	3.6e-36				
	N I	$2s^2 2p^2 (^3P) 3p$	$3/2$	$2s^2 2p^2 (^3P) 4d$	$4P$	$4P$	675.20	4.3e-30				
	Fe I	$3d^6 (^3D) 4s 4p (^1P^\circ)$	1	$3d^6 (^3D) 4s (^4D) 5s$	1	$g^5 D$	675.27	4.0e-23			675.91	1.9e-22
	Fe II	$3d^6 (^3D) 4d$	$3/2$	$3d^6 (^3D) 4f$	$3/2$	$2[3]^\circ$	675.72	1.0e-32				4.0e-21
	N I	$2s^2 2p^2 (^3P) 3p$	$5/2$	$2s^2 2p^2 (^3P) 4d$	$4P$	$4P$	675.92	4.2e-30				
	Ni I	$3d^{10}$	0	$3d^9 (^2D_{5/2}) 4p$	$3P^\circ$	$3P^\circ$	676.78	6.2e-22	676.78	1.2e-21	676.94	7.1e-22
	Ni I	$2s^2 2p^2 (^3P) 3p$	$5/2$	$2s^2 2p^2 (^3P) 4d$	$4P$	$4P$	676.96	9.9e-30				
	Fe II	$3d^6 (^3D) 5p$	$7/2$	$3d^6 (^3D) 5d$	$7/2$	$6G$	677.09	2.1e-32				
	Ni I	$3d^9 (^2D_{5/2}) 4p$	1	$3d^9 (^2D_{5/2}) 5s$	2	$2[3/2]$	677.23	4.7e-23				
F26	Fe II	$3d^6 (^3D) 5p$	$1/2$	$3d^6 (^3D) 5d$	$3/2$	$4P$	677.72	6.0e-33			678.12	3.2e-21
	Mg II	$2p^6 5p$	$1/2$	$2p^6 7d$	$3/2$	2D	678.14	1.9e-32				
	Fe I	$3d^7 (^4F) 4p$	2	$3d^7 (^4F) 5s$	3	$e^3 F$	678.69	2.3e-23	678.72	1.0e-22	678.78	5.4e-21
	Mg II	$2p^6 5p$	$3/2$	$2p^6 7d$	$5/2$	2D	678.79	3.3e-32				
	N I	$2s^2 2p^2 (^3P) 3p$	$5/2$	$2s^2 2p^2 (^3P) 5s$	$4P$	$4P$	694.52	2.5e-29	694.52	2.7e-21	694.52	1.8e-20
	Fe I	$3d^6 4s^2$	1	$3d^6 (^5D) 4s 4p (^3P^\circ)$	2	$z^3 P^\circ$	694.52	1.4e-21				
	N I	$2s^2 2p^2 (^3P) 3p$	$1/2$	$2s^2 2p^2 (^3P) 5s$	$4P$	$4P$	695.16	9.7e-30	695.17	4.9e-22	695.24	2.6e-20
	Fe II	$3d^6 (^3D) 5p$	$5/2$	$3d^6 (^3D) 5d$	$7/2$	$4G$	695.27	1.2e-31				
	N I	$2s^2 2p^2 (^3P) 3p$	$3/2$	$2s^2 2p^2 (^3P) 5s$	$4P$	$4P$	696.05	4.4e-30				
	Fe I	$3d^8$	2	$3d^6 (^3G) 4s 4p (^3P^\circ)$	3	$v^5 F^\circ$	696.30	1.2e-22	696.23	4.2e-22		
F27	Fe II	$3d^6 (^3D) 5p$	$3/2$	$3d^6 (^3D) 5d$	$4D$	$4D$	697.58	2.3e-32				
	Si I	$3s^2 3p 4p$	1	$3s^2 3p 6d$	3	$3F^\circ$	697.65	7.3e-24				
	Cr I	$3d^4 (^3D) 4s 4p (^3P^\circ)$	4	$3d^5 (^6S) 4d$	5	$e^7 D$	697.84	1.2e-21			697.84	7.9e-21
	Fe I	$3d^6 4s^2$	0	$3d^6 (^3D) 4s 4p (^3P^\circ)$	1	$z^3 P^\circ$	697.89	1.1e-21				
	N I	$2s^2 2p^2 (^3P) 3p$	$5/2$	$2s^2 2p^2 (^3P) 5s$	$4P$	$4P$	697.92	9.2e-30				
	Cr I	$3d^4 (^3D) 4s 4p (^3P^\circ)$	4	$3d^5 (^6S) 4d$	4	$e^7 D$	697.98	3.3e-22

Fig. B.2. Spectral features F7–F12. *Upper part:* synthetic spectra calculated under different temperatures: blue shows 4000 K, green shows 7000 K, and red shows 10000 K. The intensity of each of these spectra is scaled to 1. *Lower part:* high-resolution emission spectrum of the meteorite laser ablation plasma. Each marked peak is listed in Table A.1

Fig. B.3. Spectral features F13–F18. *Upper part:* synthetic spectra calculated under different temperatures: blue shows 4000 K, green shows 7000 K, and red shows 10 000 K. The intensity of each of these spectra is scaled to 1. *Lower part:* high-resolution emission spectrum of the meteorite laser ablation plasma. Each marked peak is listed in Table A.1

Fig. B.4. Spectral features F19–F24. *Upper part:* synthetic spectra calculated under different temperatures: blue shows 4000 K, green shows 7000 K, and red shows 10 000 K. The intensity of each of these spectra is scaled to 1. *Lower part:* high-resolution emission spectrum of the meteorite laser ablation plasma. Each marked peak is listed in Table A.1

Fig. B.5. Spectral features F25–F26. *Upper part:* synthetic spectra calculated under different temperatures: blue shows 4000 K, green shows 7000 K, and red shows 10000 K. The intensity of each of these spectra is scaled to 1. *Lower part:* high-resolution emission spectrum of the meteorite laser ablation plasma. Each marked peak is listed in Table A.1

Appendix C: Simulation spectra of chondrite meteorites

Fig. C.1. Low-resolution simulation spectra of chondrite meteorites for gradually increasing temperatures.