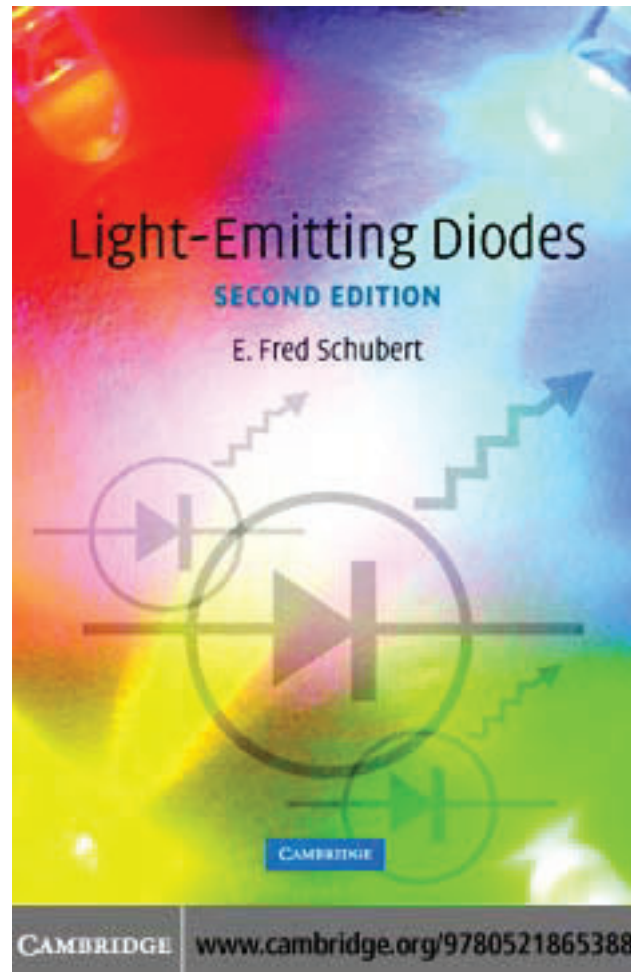




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LIGHT-EMITTING DIODES

SECOND EDITION

Revised and fully updated, the Second Edition of this textbook offers a comprehensive explanation of the technology and physics of light-emitting diodes (LEDs) such as infrared, visible-spectrum, ultraviolet, and white LEDs made from III–V semiconductors. The elementary properties of LEDs such as electrical and optical characteristics are reviewed, followed by the analysis of advanced device structures.

With nine additional chapters, the treatment of LEDs has been vastly expanded, including new material on device packaging, reflectors, UV LEDs, III–V nitride materials, solid-state sources for illumination applications, and junction temperature. Radiative and non-radiative recombination dynamics, methods for improving light extraction, high-efficiency and high-power device designs, white-light emitters with wavelength-converting phosphor materials, optical reflectors, and spontaneous recombination in resonant-cavity structures, are discussed in detail. Fields related to solid-state lighting such as human vision, photometry, colorimetry, and color rendering are covered beyond the introductory level provided in the first edition. The applications of infrared and visible-spectrum LEDs in silica fiber, plastic fiber, and free-space communication are also discussed. Semiconductor material data, device design data, and analytic formulae governing LED operation are provided.

With exercises, solutions and illustrative examples, this textbook will be of interest to scientists and engineers working on LEDs, and to graduate students in electrical engineering, applied physics, and materials science.

Additional resources for this title are available online at www.cambridge.org/9780521865388.

E. FRED SCHUBERT received his Ph.D. degree with Honors in Electrical Engineering from University of Stuttgart in 1986 and is currently a Wellfleet Senior Constellation Professor of the Future Chips Constellation at Rensselaer Polytechnic Institute. He has made several pioneering contributions to the field of LEDs, including the first demonstration of the resonant-cavity light-emitting diode (RCLED). He has authored or co-authored more than 200 publications including *Doping in III–V Semiconductors* (Cambridge University Press, 1993, 0-521-01784-X) for which he was awarded the VDE Literature Prize. He is inventor or co-inventor of 28 US Patents and a Fellow of the IEEE, APS, OSA, and SPIE. He received the Senior Research Award of the Humboldt Foundation, the Discover Award for Technological Innovation, the RD 100 Award, and Boston University's Provost Innovation Fund Award.

Note: This book contains many figures in which color adds important information. For this reason, all figures are available in color on the Internet at the following websites: <<http://www.cambridge.org/9780521865388>> and <<http://www.LightEmittingDiodes.org>>.

LIGHT-EMITTING DIODES

SECOND EDITION

E. FRED SCHUBERT

*Rensselaer Polytechnic Institute,
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Preface

During the last four decades, technical progress in the field of light-emitting diodes (LEDs) has been breathtaking. State-of-the art LEDs are small, rugged, reliable, bright, and efficient. At this time, the success story of LEDs still is in full progress. Great technological advances are continuously being made and, as a result, LEDs play an increasingly important role in a myriad of applications. In contrast to many other light sources, LEDs have the potential of converting electricity to light with near-unit efficiency.

LEDs were discovered by accident in 1907 and the first paper on LEDs was published in the same year. LEDs became forgotten only to be re-discovered in the 1920s and again in the 1950s. In the 1960s, three research groups, one working at General Electric Corporation, one at MIT Lincoln Laboratories, and one at IBM Corporation, pursued the demonstration of the semiconductor laser. The first viable LEDs were by-products in this pursuit. LEDs have become devices in their own right and today possibly are the most versatile light sources available to humankind.

The first edition of this book was published in 2003. The second edition of the book is expanded by the discussion of additional technical areas related to LEDs including optical reflectors, the assessment of LED junction temperature, packaging, UV emitters, and LEDs used for general lighting applications. No different than the first edition, the second edition is dedicated to the technology and physics of LEDs. It reviews the electrical and optical fundamentals of LEDs, materials issues, as well as advanced device structures. Recent developments, particularly in the field of III–V nitrides, are also discussed. The book mostly discusses LEDs made from III–V semiconductors. However, much of the science and technology discussed is relevant to other solid-state light emitters such as group-IV, II–VI, and organic emitters. Several application areas of LEDs are discussed in detail, including illumination and communication applications.

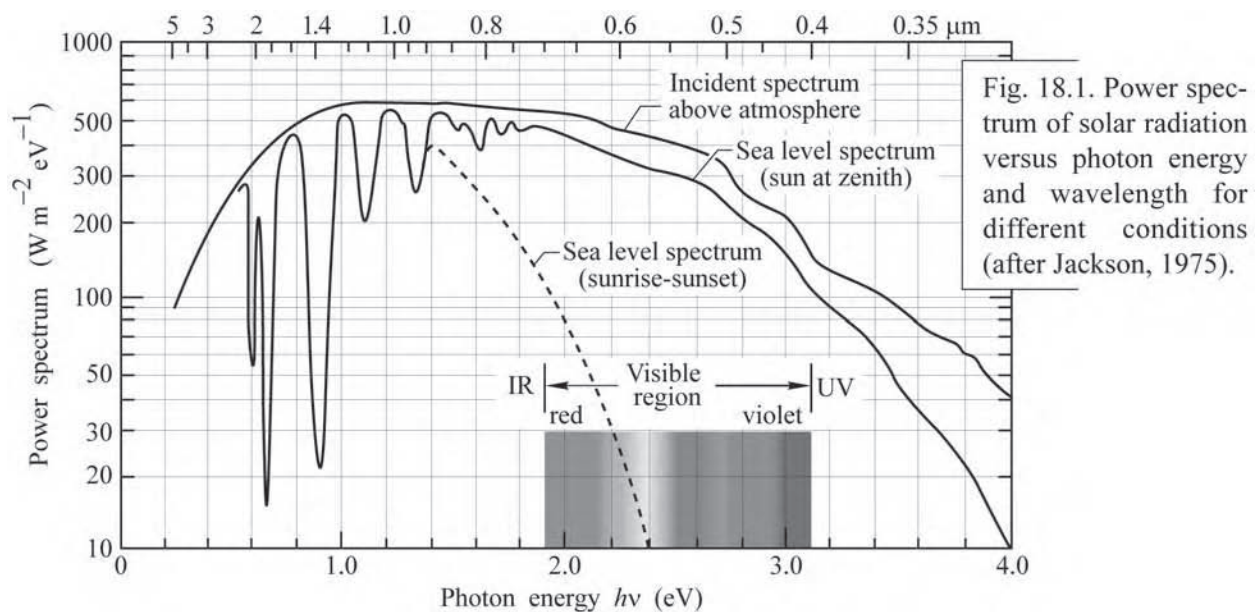
Many colleagues and collaborators have provided information not readily available and have given valuable suggestions on the first and second editions of this book. In particular, I am deeply grateful to Enrico Bellotti (Boston University), Jaehae Cho (Samsung Advanced Institute of Technology), George Craford (LumiLeds Corp.), Thomas Gessmann (RPI), Nick Holonyak Jr. (University of Illinois), Jong Kyu Kim (RPI), Mike Krames (LumiLeds Corp.), Shawn Lin (RPI), Ralph Logan (retired, formerly with AT&T Bell Laboratories), Fred Long (Rutgers University), Paul Maruska (Crystal Photonics Corp.), Gerd Mueller (LumiLeds Corp.), Shuji Nakamura (University of California, Santa Barbara), N. Narendran (RPI), Yoshihiro Ohno (National Institute of Standards and Technology), Jacques Pankove (Astralux Corp.), Yongjo Park (Samsung Advanced Institute of Technology), Manfred Pilkuhn (retired, University of Stuttgart, Germany), Hans Rupprecht (retired, formerly with IBM Corp.), Michael Shur (RPI), Cheolsoo Sone (Samsung Advanced Institute of Technology), Klaus Streubel (Osram Opto Semiconductors Corp., Germany), Li-Wei Tu (National Sun Yat-Sen University, Taiwan), Christian Wetzel (RPI), Jerry Woodall (Yale University), and Walter Yao (Advanced Micro Devices Corp.). I would also like to thank my current and former post-doctoral fellows and students for their many significant contributions to this book.

Planckian sources and color temperature

White light is a unique color. There are a very large number of optical spectra that can be used to generate white light. Among these spectra, the planckian black-body radiation spectrum forms a unique and very useful standard because it allows us to describe the spectrum with only one parameter, namely the color temperature. Furthermore, natural daylight closely resembles the planckian spectrum.

18.1 The solar spectrum

White light usually has a broad spectrum extending over the entire visible range. An instructive model for white light is sunlight. The sun's optical spectrum is shown in Fig. 18.1, including the spectrum at sea level with the sun at zenith, incident above the earth's atmosphere, and at sunset and sunrise (Jackson, 1975). The spectrum of sunlight extends over the entire visible region. However, the sun's spectrum depends on the time of day, season, altitude, weather, and other factors.

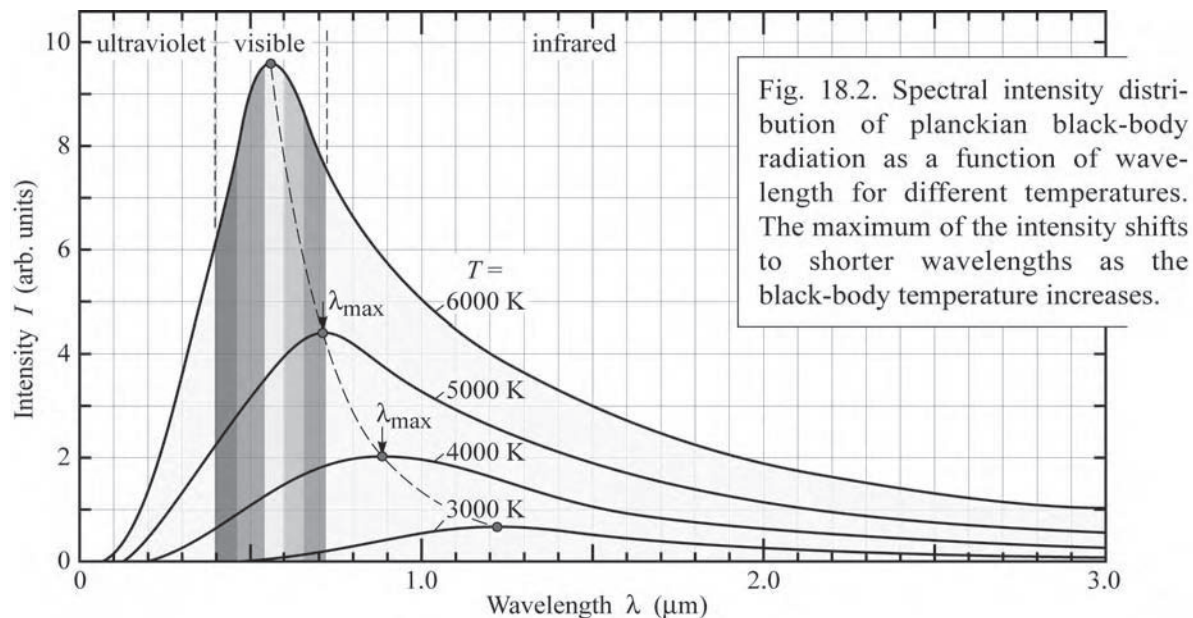


Exact replication of the solar spectrum for white-light illumination sources would not yield an efficient source due to the large infrared (IR) and ultraviolet (UV) components of the solar spectrum. Thus, “mother nature” does not serve as a good example for an efficient white source. Even if the IR and UV components of the spectrum were to be eliminated, the solar spectrum still would not be optimum, due to the high intensity at the visible-IR and visible-UV boundaries.

18.2 The planckian spectrum

It is desirable to define an independent standard for white light. The **planckian black-body radiation spectrum** is used as one such standard. The black-body spectrum is characterized by only one parameter, the temperature of the body. The black-body spectrum was first derived by Max Planck (1900) and is given by

$$I(\lambda) = \frac{2hc^2}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1 \right]} \quad (18.1)$$

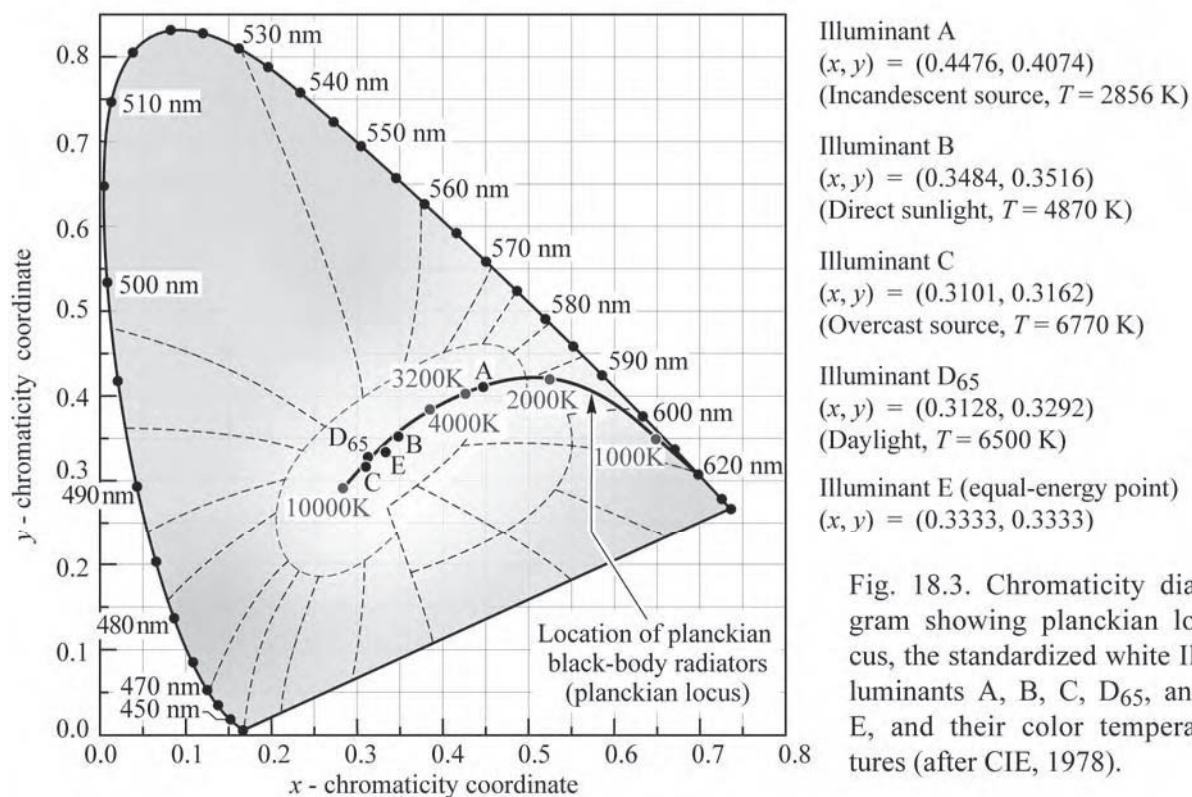


The planckian spectrum is shown for different black-body temperatures in Fig. 18.2. The maximum intensity of radiation emanating from a black body of temperature T occurs at a specific wavelength which is given by **Wien's law**

$$\lambda_{\max} = \frac{2880 \mu\text{m K}}{T} . \quad (18.2)$$

At “low” black-body temperatures, e.g. 3 000 K, the radiation occurs mostly in the infrared. As the temperature increases, the maximum of the radiation shifts into the visible wavelength range.

The location of the black-body radiation in the (x, y) chromaticity diagram (called planckian locus) is shown in Fig. 18.3. As the temperature of the black body increases, the chromaticity location moves from the red wavelength range towards the center of the diagram. Typical black-body temperatures in the white region of the chromaticity diagram range between 2 500 and 10 000 K. Also shown in Fig. 18.3 are the locations of several illuminants standardized by the CIE. These standard illuminants include Illuminants A, B, C, D₆₅, and E. The planckian locus and the locations of the black-body temperatures in the (u', v') uniform chromaticity diagram are shown in Fig. 18.4. The (x, y) and in (u', v') chromaticity coordinates of the planckian radiator are tabulated in Appendix 18.1.



In both the (x, y) and the (u', v') chromaticity diagrams, the planckian locus starts out in the red, then moves through the orange and yellow, to finally the white region. This sequence of colors is reminiscent of the colors of a real object (e.g. a piece of metal) heated to high

temperatures, indicating that real objects closely follow the chromaticity of Planck's idealized black bodies.

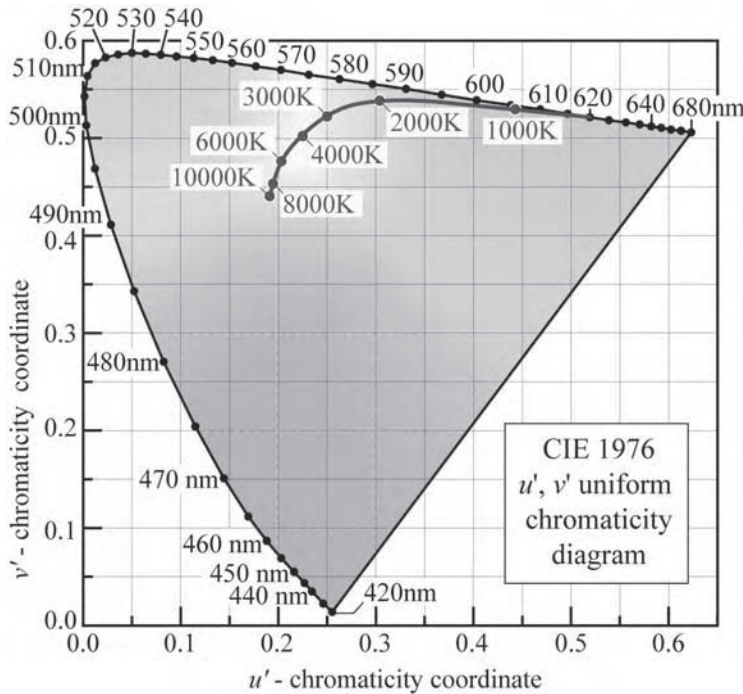


Fig. 18.4. CIE 1976 (u' , v') uniform chromaticity diagram calculated using the CIE 1931 2° standard observer and planckian locus.

18.3 Color temperature and correlated color temperature

Color temperature may appear to be a somewhat surprising quantity as *color* and *temperature* don't seem to have a direct relationship with each other. However, the relationship is derived from Planck's black-body radiator. With increasing temperatures, it glows in the red, orange, yellowish white, white, and ultimately bluish white. The **color temperature** (CT) of a white light source, given in units of kelvin, is the temperature of a planckian black-body radiator that has the same chromaticity location as the white light source considered.

If the color of a white light source does not fall on the planckian locus, the **correlated color temperature** (CCT), also given in units of kelvin, is used. The correlated color temperature of a white light source is defined as the temperature of a planckian black-body radiator whose color is closest to the color of the white light source.

The correlated color temperature of a light source is determined as follows. On the (u', v') uniform chromaticity diagram, the point on the planckian locus that is *closest* to the chromaticity location of the light source is determined (i.e. shortest geometrical distance). The correlated color temperature is the temperature of the planckian black-body radiator at that point. The

determination of the correlated color temperature was discussed in CIE publication No. 17.4 (1987) and by Robertson (1968).

On the (x, y) chromaticity diagram, the correlated color temperature *cannot* be determined by using the shortest distance to the planckian locus due to the non-uniformity of the (x, y) chromaticity diagram. The lines of constant correlated color temperature in the (x, y) chromaticity diagram are shown in Fig. 18.5 (Duggal, 2005).

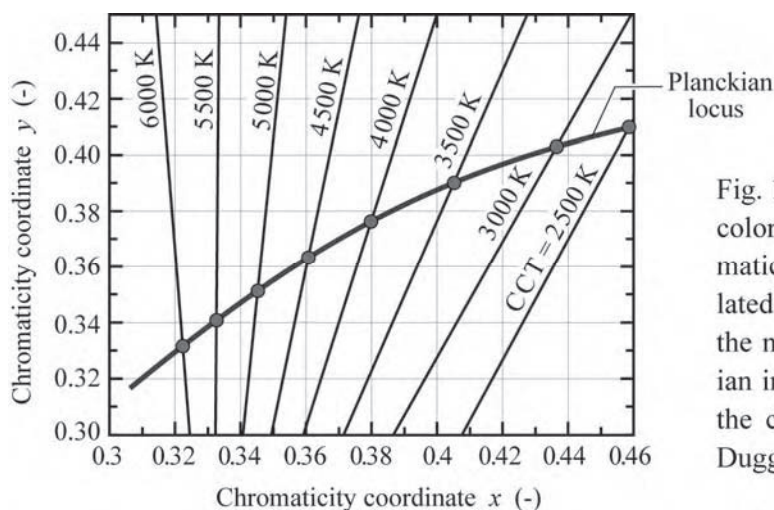


Fig. 18.5. Lines of constant correlated color temperature in the (x, y) chromaticity diagram. Whereas the correlated color temperature follows from the minimum distance to the planckian in the (u', v') diagram, this is not the case in the (x, y) diagram (after Duggal, 2005).

Table 18.1. Correlated color temperatures of common artificial and natural light sources.

Light source	Correlated color temperature (K)
Wax candle flame / CIE standard candle flame	1 500 to 2 000 / 2 000
W filament household lamp: 60 W / 100 W	2 800 / 2 850
W filament halogen lamp	2 800 to 3 200
“Warm white” fluorescent tube	3 000
“Cool daylight white” fluorescent tube	4 300
“True daylight” color match fluorescent tube	6 500
Carbon arc white flame	5 000
Xenon arc (unfiltered)	6 000
Summer sunlight (before 9.00 or after 15.00 h)	4 900 to 5 600
Summer sunlight (9.00 to 15.00 h)	5 400 to 5 700
Direct sun	5 700 to 6 500
Overcast daylight	6 500 to 7 200
Clear blue sky	8 000 to 27 000

The chromaticity locations of incandescent light sources are very close to, although not exactly on the planckian locus (Ohno, 2001). For such incandescent light sources, the *color temperature* can be specified. Standard incandescents have color temperatures ranging from 2 000 to 2 900 K. The common warm incandescent light source has a color temperature of 2 800 K. Quartz halogen incandescent lamps have a color temperature ranging from 2 800 to 3 200 K (Ohno, 1997). Other light sources, such as metal-halide sources, are further removed from the planckian locus. For such light sources, the *correlated color temperature* should be used. Bluish white lights have a correlated color temperature of about 8 000 K. Color temperatures and correlated color temperatures of common artificial and natural light sources are given in Table 18.1.

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Appendix 18.1Color temperature T and (x, y) and (u', v') chromaticity coordinates of a planckian emitter.

T	x	y	u'	v'
1 000 K	0.649	0.347	0.443	0.533
1 200 K	0.623	0.370	0.402	0.538
1 400 K	0.597	0.389	0.369	0.541
1 600 K	0.572	0.402	0.342	0.542
1 800 K	0.549	0.412	0.321	0.542
2 000 K	0.527	0.417	0.303	0.540
2 200 K	0.506	0.420	0.288	0.538
2 400 K	0.487	0.419	0.276	0.535
2 600 K	0.470	0.417	0.266	0.531
2 800 K	0.454	0.414	0.257	0.528
3 000 K	0.439	0.409	0.250	0.524
3 200 K	0.425	0.404	0.243	0.520
3 400 K	0.413	0.399	0.237	0.516
3 600 K	0.402	0.393	0.233	0.512
3 800 K	0.392	0.388	0.228	0.508
4 000 K	0.383	0.382	0.225	0.504
4 200 K	0.374	0.376	0.221	0.500
4 400 K	0.367	0.371	0.218	0.497
4 600 K	0.360	0.366	0.216	0.494
4 800 K	0.353	0.361	0.213	0.490
5 000 K	0.347	0.356	0.211	0.487
5 200 K	0.342	0.351	0.209	0.484
5 400 K	0.337	0.347	0.208	0.481
5 600 K	0.332	0.343	0.206	0.479
5 800 K	0.328	0.339	0.205	0.476
6 000 K	0.324	0.335	0.203	0.473
6 200 K	0.321	0.332	0.202	0.471
6 400 K	0.317	0.328	0.201	0.469
6 500 K	0.315	0.327	0.201	0.468
6 600 K	0.314	0.325	0.200	0.466
6 800 K	0.311	0.322	0.199	0.464
7 000 K	0.308	0.319	0.198	0.462
7 200 K	0.306	0.317	0.198	0.460
7 400 K	0.303	0.314	0.197	0.459
7 600 K	0.301	0.312	0.196	0.457
7 800 K	0.299	0.309	0.196	0.455
8 000 K	0.297	0.307	0.195	0.454
8 500 K	0.292	0.301	0.194	0.450
9 000 K	0.289	0.297	0.193	0.447
9 500 K	0.285	0.293	0.192	0.444
10 000 K	0.282	0.290	0.191	0.441