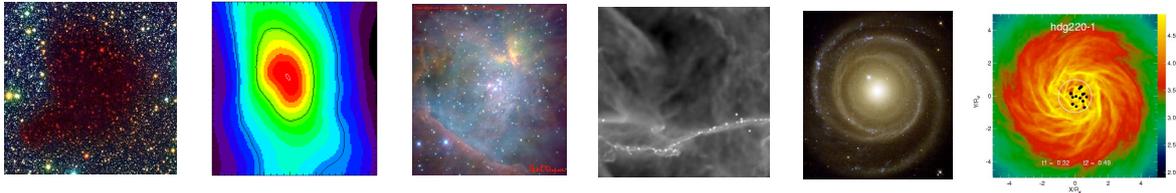


# Sterne



**Ralf Klessen**

Zentrum für Astronomie der Universität Heidelberg



28.11.2012

## Literatur über Sterne

### ● Liste von empfohlenen Büchern

- Carroll, B.W., & Ostlie, D. A. 1996, "An Introduction into Modern Stellar Astrophysics" (Addison Wesley) -- Chapters 7 - 17
- Clayton, D. D. 1968, "Principles of Stellar Evolution and Nucleosynthesis" (McGraw-Hill, New York)
- Hansen, C.J., & Kawaler, S.D. 1994, "Stellar Interiors: Physical Principles, Structure, and Evolution" (Springer Verlag, Heidelberg Berlin New York)
- Kippenhahn, R., & Weigert, A. 1990, "Stellar Structure and Evolution" (Springer Verlag, Heidelberg Berlin New York)
- Phillips, A. C. 2006, The Physics of Stars (Wiley, second edition)
- Prialnik, D. 2010, An Introduction to the Theory of Stellar Structure and Evolution (Cambridge Univ. Press, second edition)
- Ryan, S. G. & Norton, A. J. 2010, Stellar Evolution and Nucleosynthesis (Cambridge University Press)
- Shore, S. N. 2003, "The Tapestry of Modern Astrophysics" (Wiley, Hoboken, New Jersey) - Chapters 3 - 5

# Allgemeine Literatur

## ● Allgemeine Bücher

- Binney, J. & Merrifield, M. 1998, "Galactic Astronomy" (Princeton University Press)
- Scheffler, H. & Elsässer, H. 1990, "Physik der Sterne und der Sonne" (BI, Mannheim Wien Zürich)
- Shu, F. 1991, "The Physical Universe: An Introduction to Astronomy" (University Science Books, Mill Valley, California)
- Shu, F. 1991, "The Physics of Astrophysics I: Radiation" (University Science Books, Mill Valley)
- Shu, F. 1991, "The Physics of Astrophysics II: Gas Dynamics" (University Science Books, Mill Valley)
- Stahler, S. W. & Palla, F. 2004, "The Formation of Stars" (Wiley-VCH, Weinheim)
- Unsöld, A. & Baschek, B. 1991, "The New Cosmos" (Springer Verlag)
- Voigt, H.-H. 2002, "Abriss der Astronomie" (Spektrum Akademischer Verlag)
- Weigert, A, Wendker, H. J., & Wisotzki, L. 2004, "Astronomie und Astrophysik" (Wiley-VCH, Berlin)

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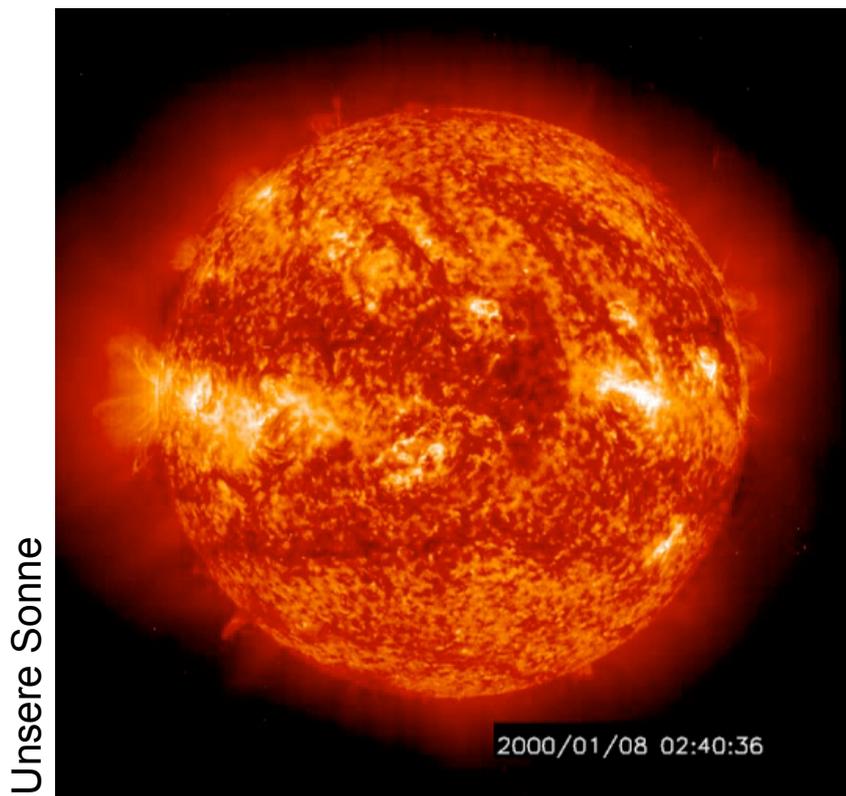
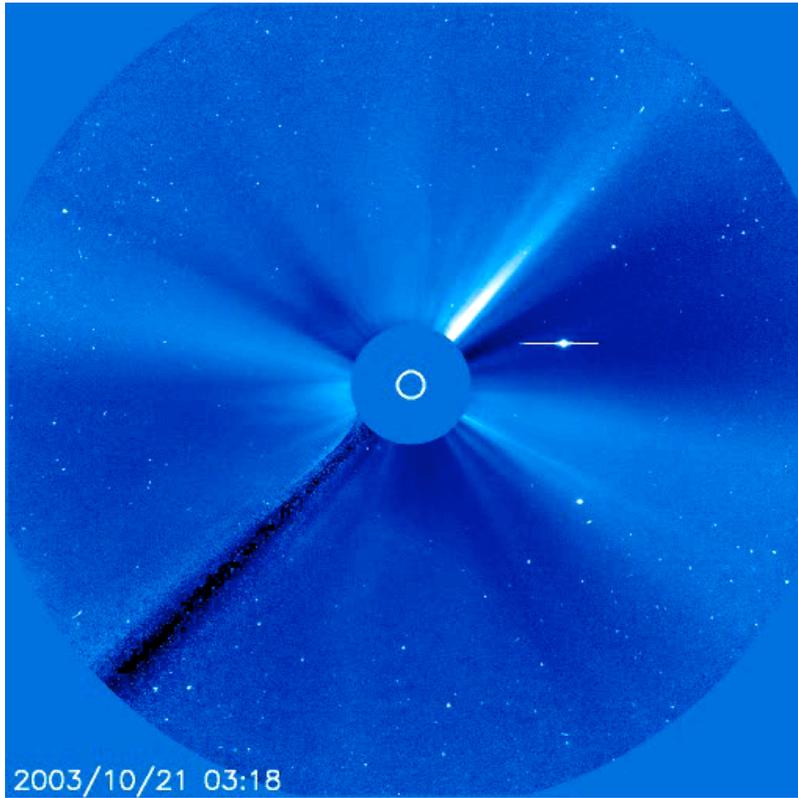


Bild: SOHO Satellit

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Unsere Sonne

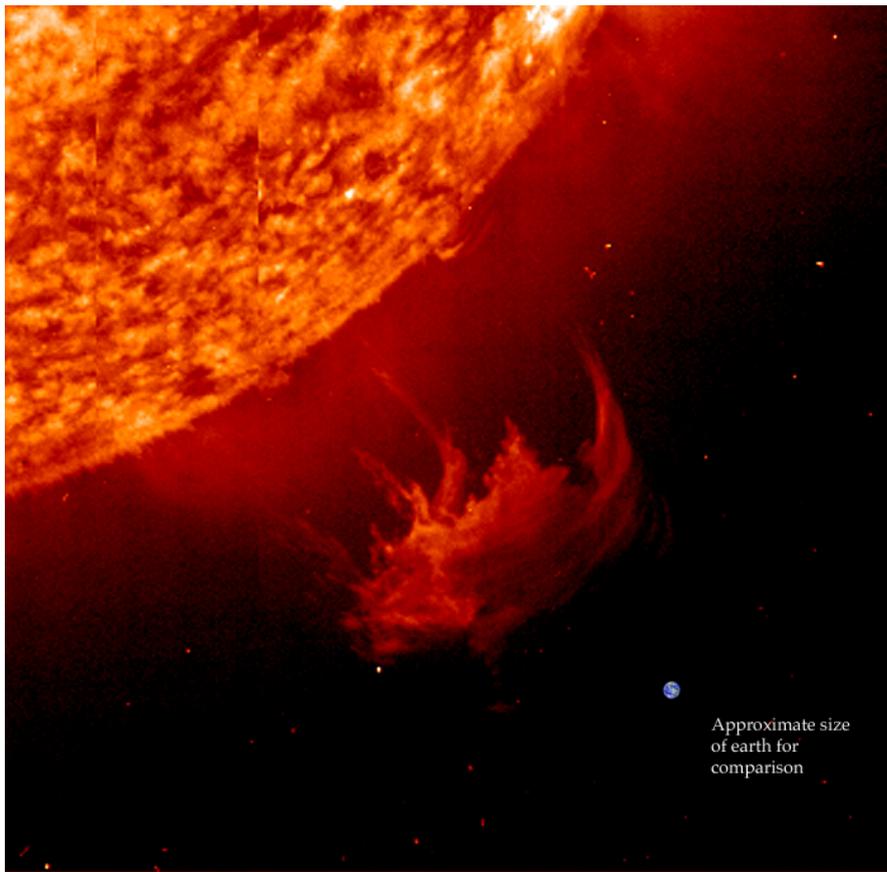


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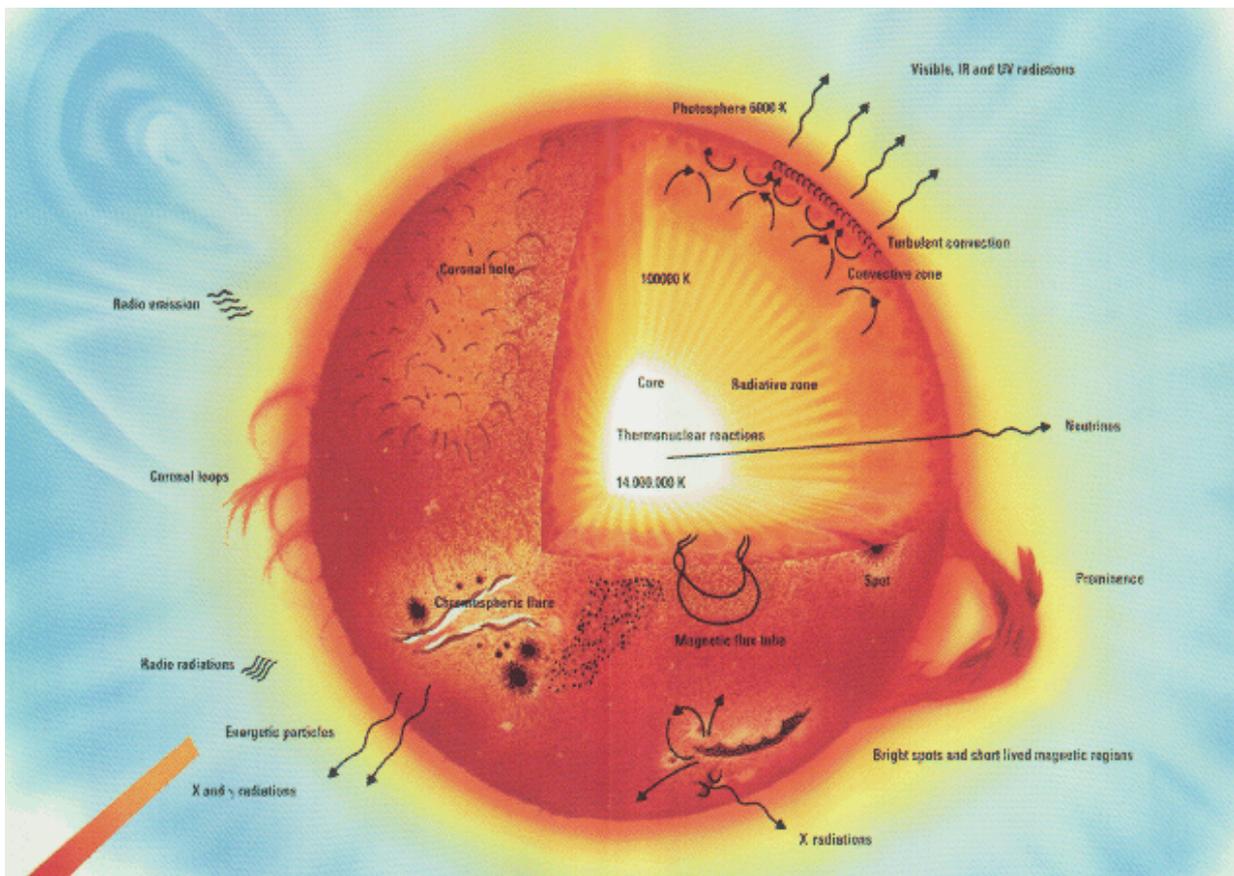
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Größenvergleich: Sonne - Erde



Approximate size  
of earth for  
comparison

28.11.2012



Bildquelle: NASA

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## Sterne: die Sonne

Eigenschaften der Sterne  
(Stellare Zustandsgrößen):



**Unsere Sonne ☉ als Referenzstern**

Radius	$R_{\odot}$	696 000 km
Masse	$M_{\odot}$	$1,989 \times 10^{30}$ kg
Leuchtkraft	$L_{\odot}$	$3,86 \times 10^{26}$ W
effektive Temperatur	$T_{\text{eff}}$	5800 K (Oberfläche)
Zentraltemperatur	$T_{\text{zentral}}$	$15 \times 10^6$ K
Alter	$t_{\odot}$	$4.5 \times 10^9$ a

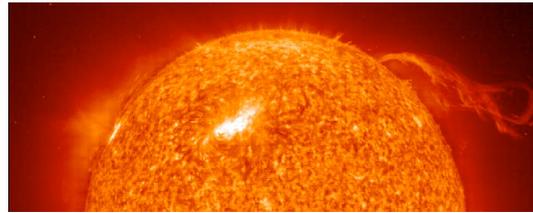
auf der Erde:  
Solarkonstante  
 $1.37 \text{ kW/m}^2$

Spektraltyp G2  
Leuchtkraftklasse V  
chemische Zusammensetzung (Massenanteil)  
73% Wasserstoff X  
25% Helium Y  
2% Metalle Z

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# Sterne: die Sonne

Eigenschaften der Sterne  
(Stellare Zustandsgrößen):



## Unsere Sonne ☉ als Referenzstern

Radius	$R_{\odot}$	$7 \times 10^{10}$ cm
Masse	$M_{\odot}$	$2 \times 10^{33}$ g
Leuchtkraft	$L_{\odot}$	$4 \times 10^{33}$ erg/s
effektive Temperatur	$T_{\text{eff}}$	5800 K
Zentraltemperatur	$T_{\text{zentral}}$	$15 \times 10^6$ K
Alter	$t_{\odot}$	$1.7 \times 10^{17}$ s

in cgs Einheiten

Spektraltyp G2  
 Leuchtkraftklasse V  
 chemische Zusammensetzung (Massenanteil)  
 73% Wasserstoff X  
 25% Helium Y  
 2% Metalle Z

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# Sterne: Statistische Charakteristika

## Massenverteilung:

minimale Masse  $\approx 0,07 M_{\odot}$

Grenze des Wasserstoffbrennens

maximale Masse  $\approx 120 M_{\odot}$

Eddington-Limit,  $F_{\text{rad}} = F_{\text{grav}}$

Ursprüngliche Massenverteilung

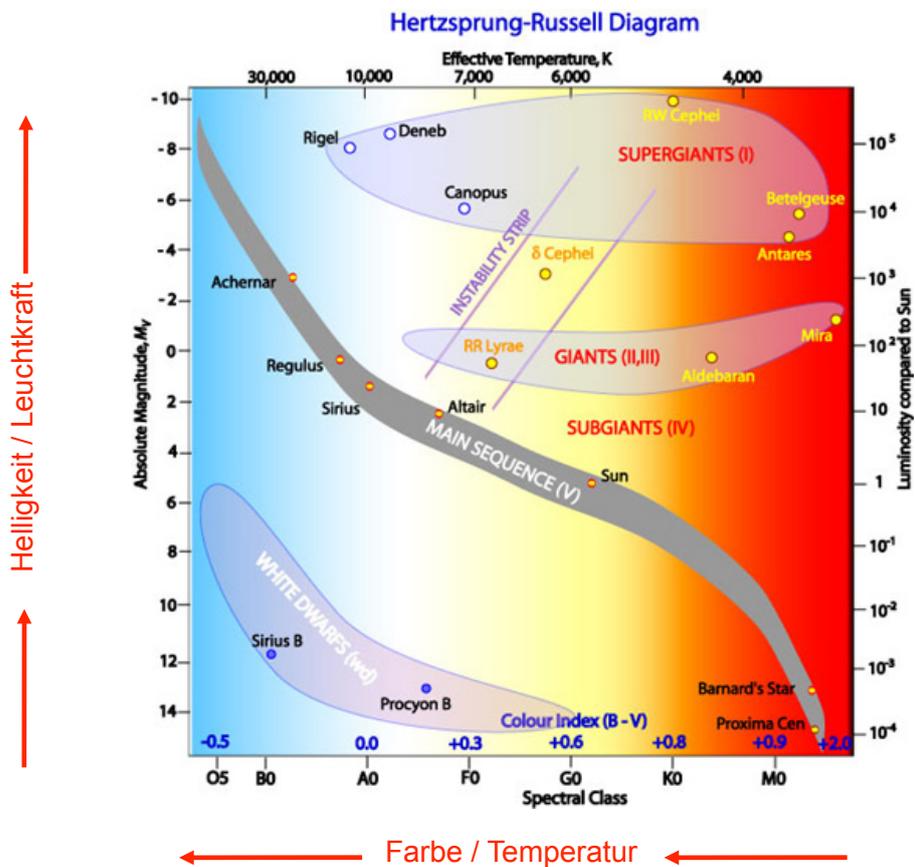
$dN(M) \propto M^{\alpha} dM$ ,  $\alpha \approx -2.3$  für Sterne massereicher als die Sonne



## Weitere Eigenschaften:

Spektraltyp	$T_{\text{eff}}$ [K]	$M[M_{\odot}]$	$L [L_{\odot}]$	$T_{\text{HR}} [a]$
O7.5	38 000	25	80 000	$2 \times 10^6$
B0	33 000	16	10 000	$1 \times 10^7$
B5	17 000	6	600	$6 \times 10^7$
A0	9 500	3	60	$3 \times 10^8$
F0	6 900	1,5	6	$1.5 \times 10^9$
G0	5 800	1	1	$6 \times 10^9$
K0	4 800	0,8	0,4	$12 \times 10^9$
M0	3 670	0,5	0,08	$35 \times 10^9$

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Bildquelle: <http://www.elektrisches-universum.de/wp-content/uploads/hrgenericssl.jpg>

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## Sterne: Statistische Charakteristika



Sterndichte in der Sonnenumgebung

$$n_* \approx 0,05 \text{ pc}^{-3}$$

Sterndichte im Orion-Trapezhaufen

$$n_* \approx 10^3 \text{ pc}^{-3}$$

Sterndichte in Starburst-Regionen

$$n_* \approx 10^4 \text{ pc}^{-3}$$

$$1 \text{ pc} = 3,086 \times 10^{18} \text{ cm}$$

**Anzahl der Sterne in der Milchstraße:**

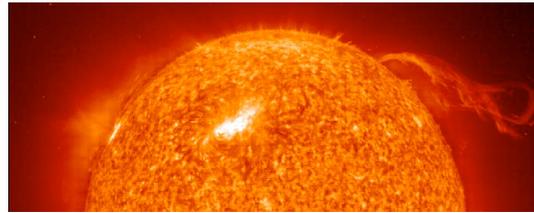
$$\approx 10^{11}$$

**Sternentstehungsrate:**

$$\approx 2 M_{\odot} / \text{Jahr}$$

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## Sterne: Statistische Charakteristika



Sterndichte in der Sonnenumgebung  
 Sterndichte im Orion-Trapezhaufen  
 Sterndichte in Starburst-Regionen

$$n_* \approx 0,05 \text{ pc}^{-3}$$

$$n_* \approx 10^3 \text{ pc}^{-3}$$

$$n_* \approx 10^4 \text{ pc}^{-3}$$

$$1 \text{ pc} = 3,086 \times 10^{18} \text{ cm}$$

<b>Anzahl der Sterne in der Milchstraße:</b>	$\approx 10^{11}$
<b>Sternentstehungsrate:</b>	$\approx 2 M_{\odot} / \text{Jahr}$

### Skalen:

Milchstraße	$\varnothing \approx 30 \text{ kpc} \approx 10^{23} \text{ cm} \approx 100.000 \text{ Lichtjahre}$
Sonnensystem (Pluto-Bahn)	$\varnothing \approx 80 \text{ AU} \approx 10^{15} \text{ cm} \approx 11 \text{ Lichtstunden}$
Erdbahn	$\varnothing \approx 2 \text{ AU} \approx 3 \times 10^{15} \text{ cm} \approx 17 \text{ Lichtminuten}$
Sonnendurchmesser	$\varnothing \approx 1,4 \times 10^{11} \text{ cm}$
Erddurchmesser	$\varnothing \approx 1,3 \times 10^9 \text{ cm}$

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## Sterne: Statistische Charakteristika



Sterndichte in der Sonnenumgebung  
 Sterndichte im Orion-Trapezhaufen  
 Sterndichte in Starburst-Regionen

$$n_* \approx 0,05 \text{ pc}^{-3}$$

$$n_* \approx 10^3 \text{ pc}^{-3}$$

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$$1 \text{ pc} = 3,086 \times 10^{18} \text{ cm}$$

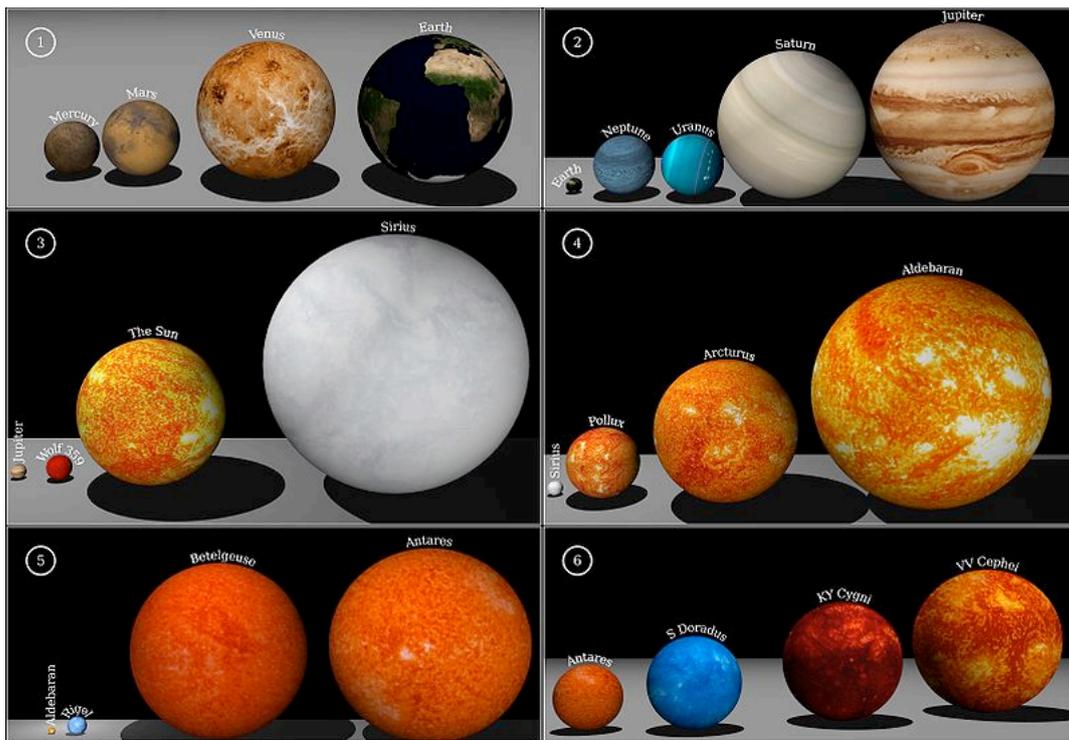
<b>Anzahl der Sterne in der Milchstraße:</b>	$\approx 10^{11}$
<b>Sternentstehungsrate:</b>	$\approx 2 M_{\odot} / \text{Jahr}$

### Skalen:

Druck im Sonneninneren	$2,5 \times 10^{11} \text{ bar} \approx 7,8 \times 10^{25} \text{ Teilchen} / \text{cm}^3$ (130 g/cm <sup>3</sup> )
Druck in Erdatmosphäre	$1013 \text{ bar} \approx 2,5 \times 10^{19} \text{ Teilchen} / \text{cm}^3$
Ultrahochvakuum (auf Erde)	$10^{-9} \text{ bar} \approx 2,5 \times 10^7 \text{ Teilchen} / \text{cm}^3$
Sternbildendes Gas	$10^3 - 10^4 \text{ Teilchen} / \text{cm}^3$
Interstellares Gas im Mittel	<i>einige</i> Teilchen / cm <sup>3</sup>

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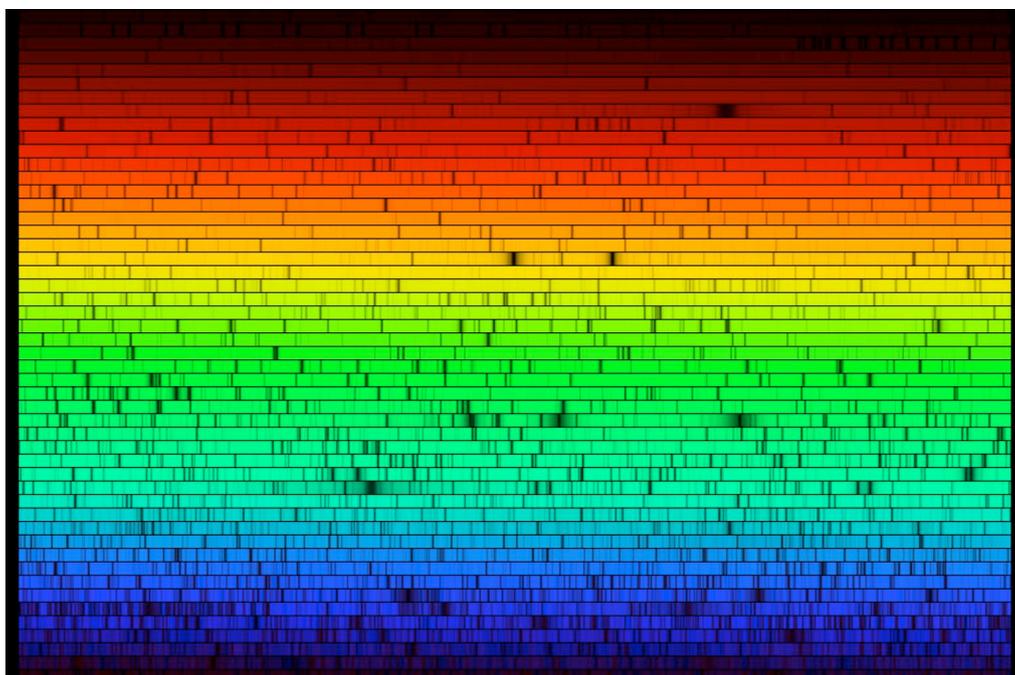
# stellar sizes



Bildquelle: Wikipedia - <http://en.wikipedia.org/wiki/File:Star-sizes.jpg>

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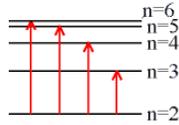
# spectrum of Sun



(Bild: NOAO)

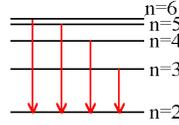
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# atomic lines



————— n=1 (Ground State)

absorption lines

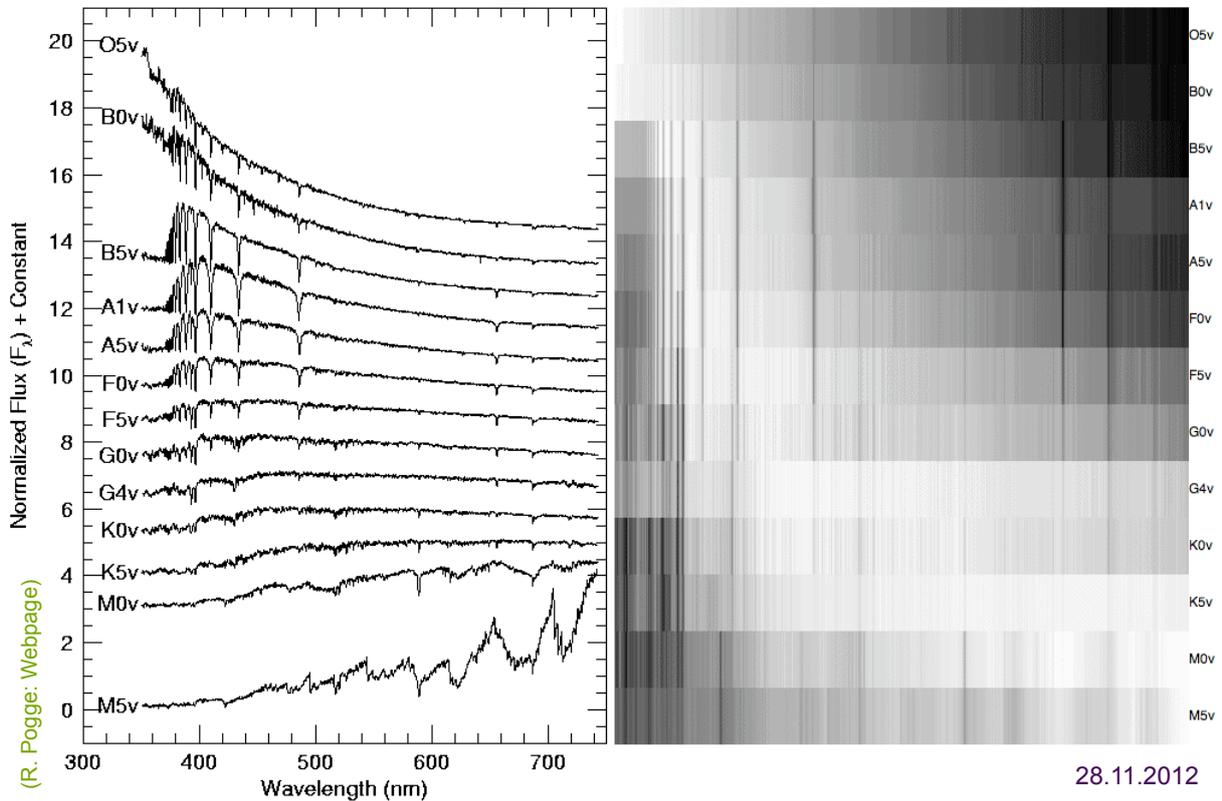


————— n=1 (Ground State)

emission lines

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# sample spectra



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**O Stars**



Hottest Stars:  $T > 30,000$  K; Strong He<sup>+</sup> lines; no H lines (or only very weak at O9).

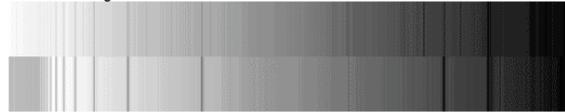


Spectrum of an O5v star

**B Stars**



$T = 11,000 - 30,000$  K; Strong neutral He lines; very weak H lines, getting stronger from B0 through B9.



Spectra of B0v (top) and B5v (bottom) stars

**B Stars**



$T = 11,000 - 30,000$  K; Strong neutral He lines; very weak H lines, getting stronger from B0 through B9.



Spectra of B0v (top) and B5v (bottom) stars

**F Stars**



$T = 5900 - 7500$  K; H grows weaker through F9, Ca<sup>+</sup> grows stronger, weak metals begin to emerge.



Spectra of F0v (top) and F5v (bottom) stars

**G Stars**



$T = 5200 - 5900$  K; Strong Ca<sup>+</sup>, Fe<sup>+</sup> and other metals dominate, H grows weaker through the class.



Spectra of G0v (top) and G4v (bottom) stars

**K Stars**



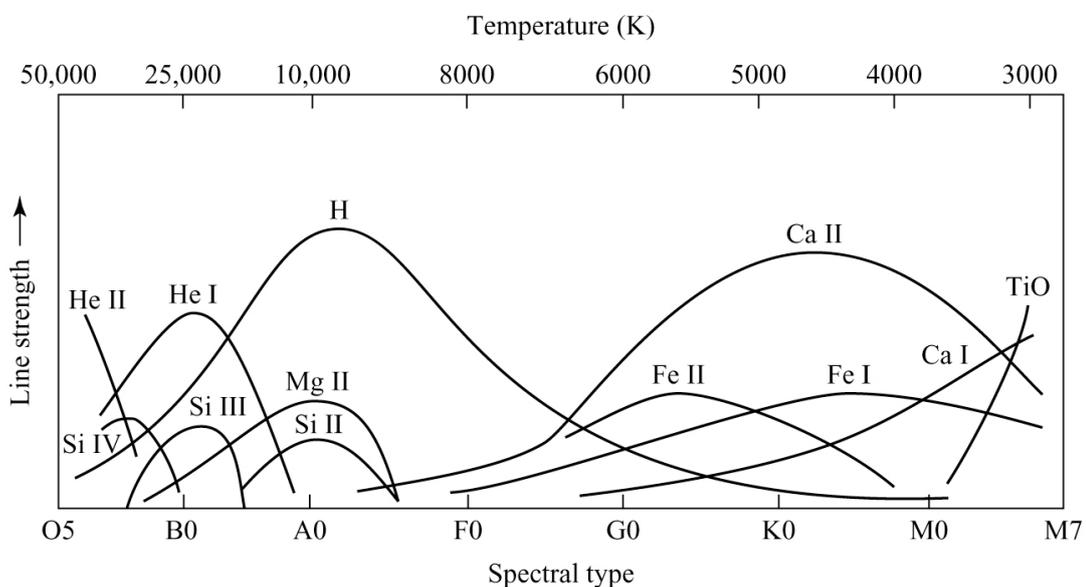
$T = 3900 - 5200$  K; Strong metal lines, weak CH & CN molecular bands begin to appear, growing through the class. H lines nearly gone.



Spectra of K0v (top) and K5v (bottom) stars

(R. Pogge: Webpage)

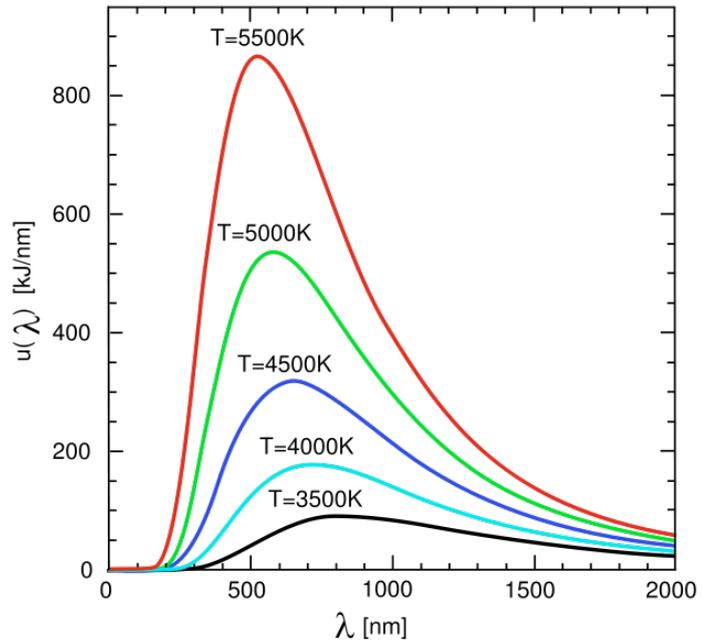
# spectroscopic classification



stars of different mass (and temperature) show different absorption and emission lines --> this can be used to build a *spectral classification scheme*

# statistical characteristics

- Hertzsprung Russell diagram: using **color** and **(absolute) magnitude**
- **spectral type** corresponds to specific **color** (and **temperature**)



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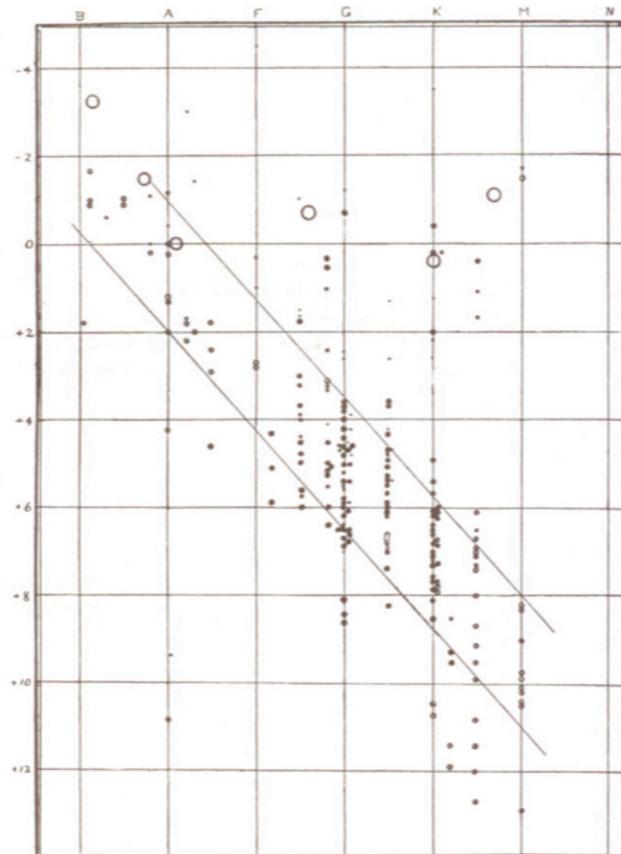
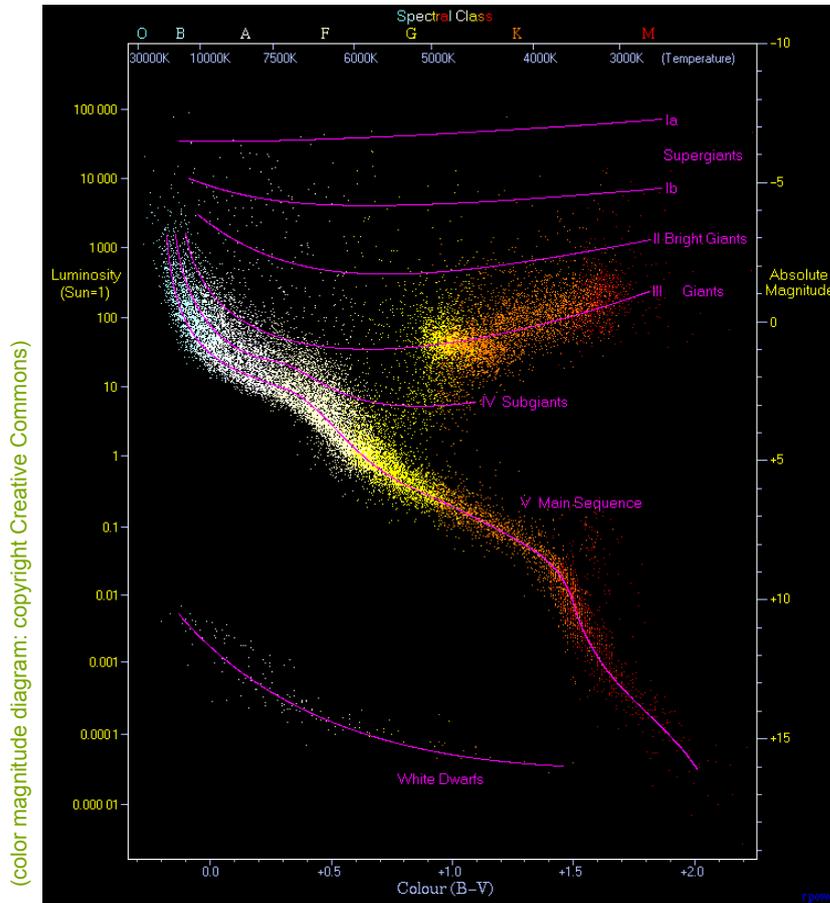


Figure 8.10 Henry Norris Russell's first diagram, with spectral types listed along the top and absolute magnitudes on the left-hand side. (Figure from Russell, *Nature*, 93, 252, 1914.)

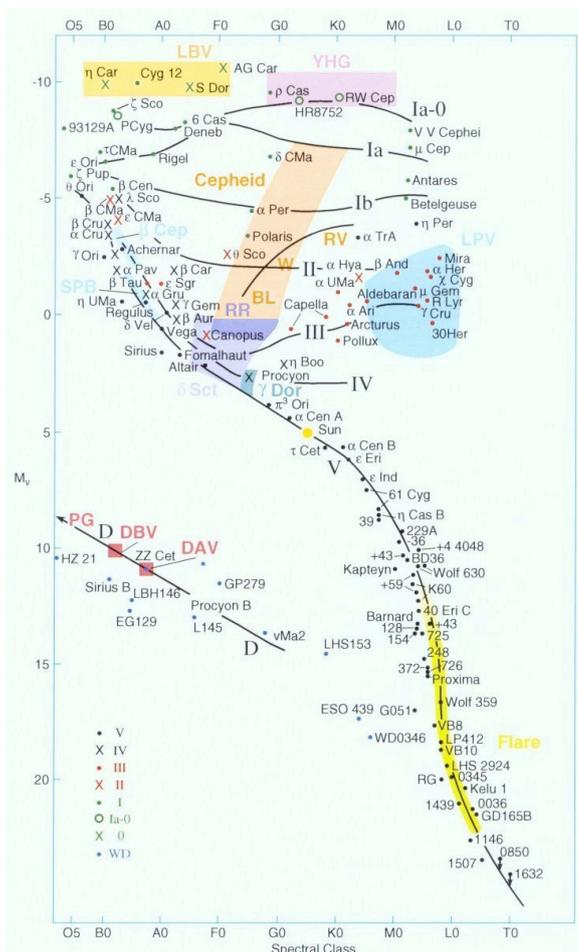
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Stellar Klassifikations-  
schema:

- supergiants (I)
- bright giants (II)
- normal giants (III)
- subgiants (IV)
- main-sequence (dwarf) stars (V)
- subdwarfs (VI)
- white dwarfs

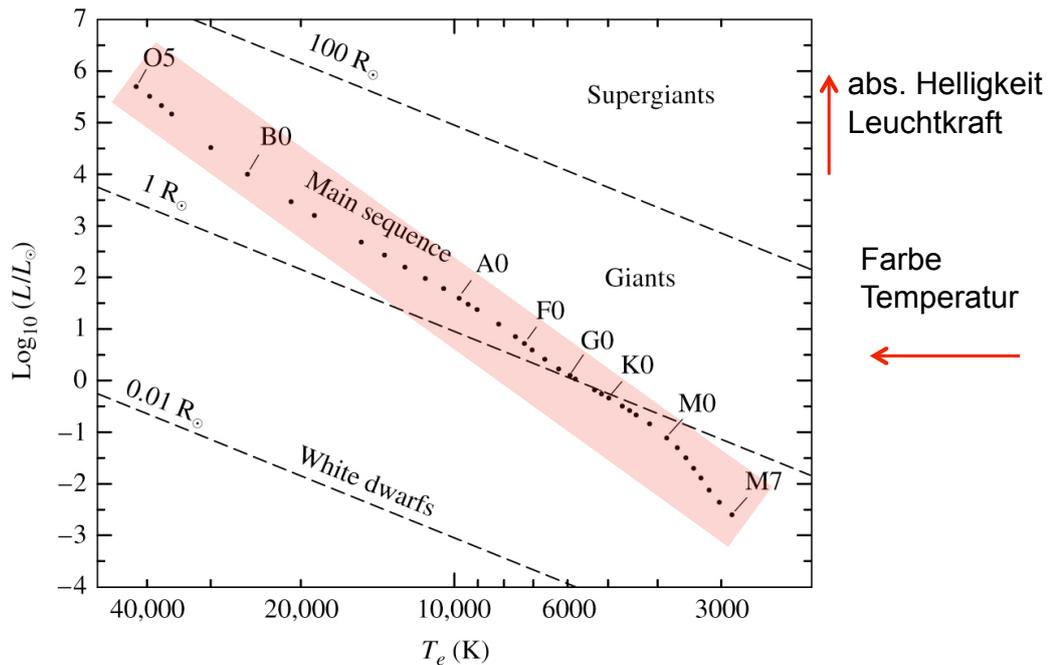
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Herzsprung Russell  
diagram with known stars  
(from Kaler: Stars and Stellar Spectra)

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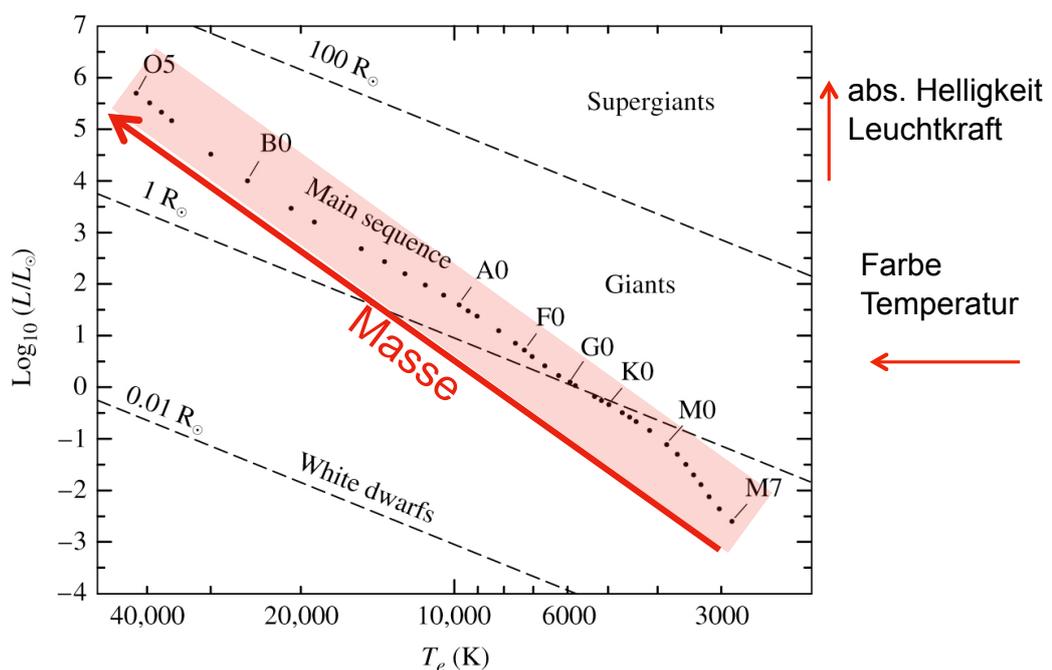
# Physikalische Interpretation



(Carroll & Ostlie: Figure 8.14)

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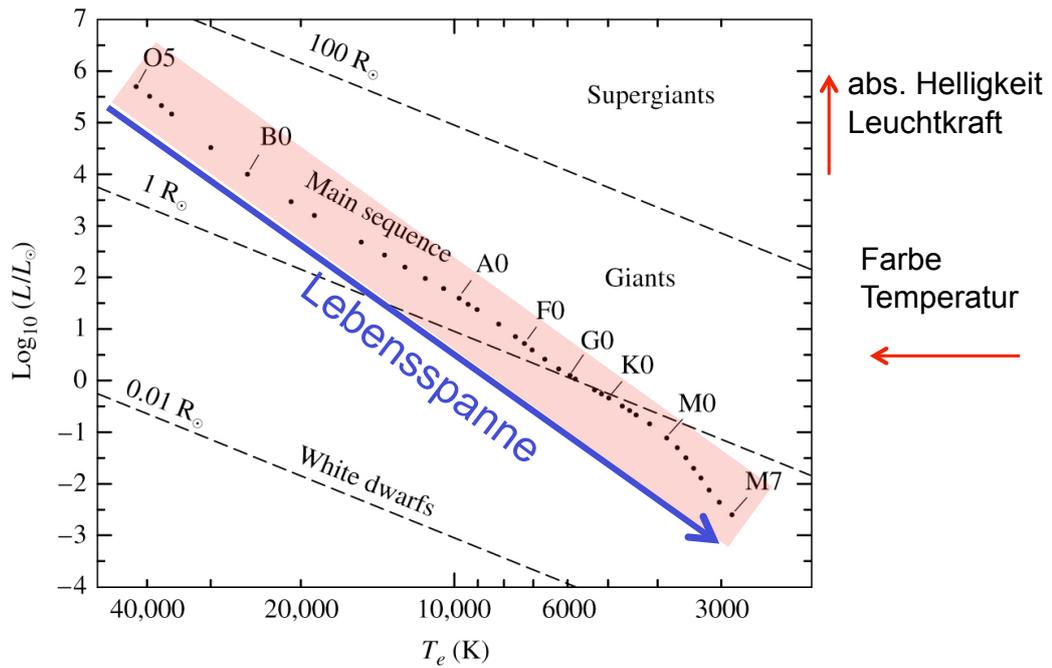
# Physikalische Interpretation



(Carroll & Ostlie: Figure 8.14)

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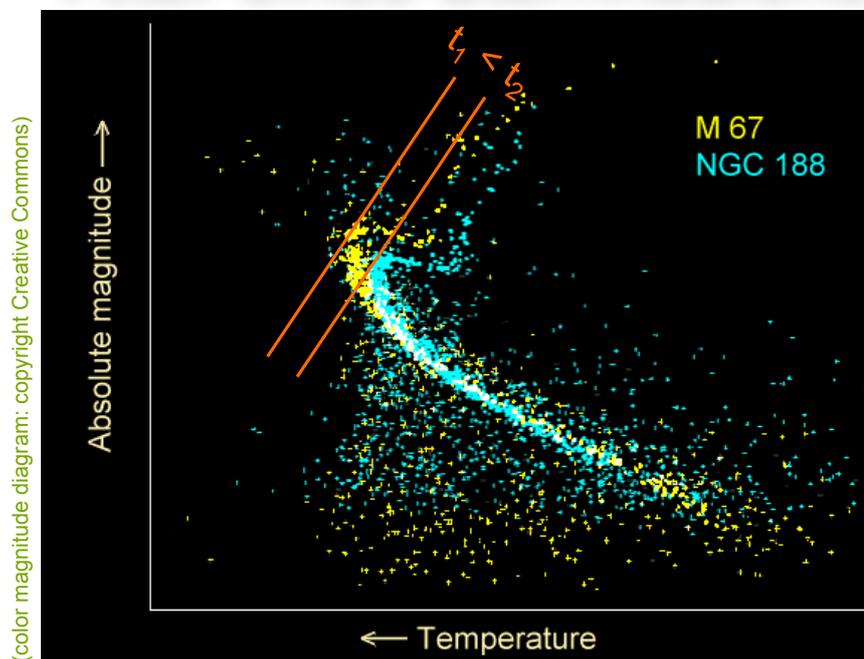
# Physikalische Interpretation



(Carroll & Ostlie: Figure 8.14)

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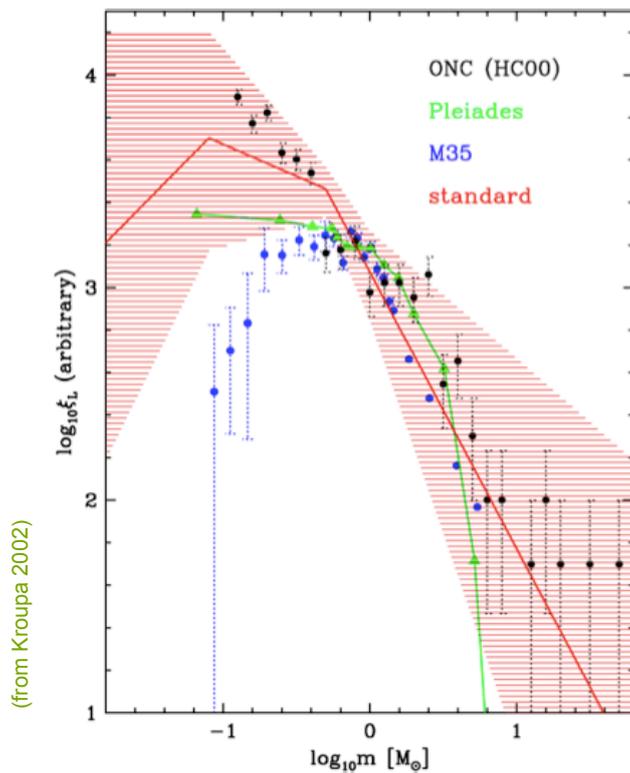
## Anwendung: Alter eines Sternhaufens



(color magnitude diagram: copyright Creative Commons)

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# distribution of stellar masses: IMF



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## Theoretische Überlegungen

- **Sternaufbaugleichungen**  
(Hydrostatik in sphärischer Symmetrie)
- **Virialsatz**
- **Zustandsgleichungen im Sterninneren**  
(ideales Gas, strahlungsdominiertes Gas, entartetes Gas)
- **Energieerzeugungsprozesse**  
(pp-Kette, CNO-Zyklus)

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