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Non-LTE models of WR winds

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Abstract. "Standard" Non-LTE models for WR winds treat the radiation transfer in a spherically-expanding, homogeneous and stationary atmosphere. These models have been widely applied for the spectral analysis of WR stars in the Galaxy and LMC. WN spectra can be well reproduced in general, while some work is still to be done on WC spectra.

Accounting for wind inhomogeneities (clumping) in a first-order approximation has significantly improved the agreement between synthetic and observed spectra with respect to the electron-scattering wings of strong lines. Spectral analyses with clumped models yield considerably lower mass-loss rates than obtained from homogeneous models. In typical models, the ionization stratification shows a stepwise recombination with increasing distance from the star.

The applied models account for complex model atoms of He and CNO elements. In a new version of our model code, line blanketing by iron-group elements is additionally included. The iron model atom is simplified by introducing superlevels and superlines, but otherwise the radiation transfer is fully treated. In first test models the radiation pressure is almost (i.e. within a factor of two) consistent with the observed acceleration of the stellar wind.

1. The state of the art

The so-called standard model for WR atmospheres is based on the simplifying assumptions of spherical symmetry, homogeneity and stationarity of the flow. The velocity law is assumed *ad hoc* (usually in the form of the so-called β law, mostly choosing $\beta = 1$), i.e. the hydrodynamic problem is not consistently solved. A specific model atmosphere is described by the following parameters: mass-loss rate $\dot{M}$, luminosity L, stellar radius R_* (taken at a defined optical depth, e.g. $\tau_{\rm Rossland} = 20$), the terminal wind velocity v_∞ and the chemical composition $X_{\rm i}$ (mass fractions). The effective temperature T_* follows from L and R_* via Stefan-Boltzmann's law.

The dominance of emission processes which depend quadratically on the density leads to an approximate degeneracy in the parameter space. With the definition of the "transformed radius" $R_{\rm t}$ (see below) it turns out that models of same R_t have nearly the same normalized spectrum (while the absolute fluxes scale with R_*^2).

Two features have been incorporated into the model calculations more recently. One concerns a first-order treatment of inhomogeneities. It is assumed that the wind consists of "clumps" in which the density is enhanced by a factor of D over the average value, while the interclump space is void (which implies that the clumps fill D^{-1} of the volume). Further it is assumed that the clumps have small size, compared to the photon's free path, which means that the radiative transfer can be treated as for a smooth medium.

The density contrast D can also be incorporated into the parameter degeneracy by defining the transformed radius as

$$R_t = R_* \left[\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \bigg/ \frac{\dot{M}\sqrt{D}}{10^{-4}\,M_\odot\,\mathrm{yr}^{-1}} \right]^{2/3} \tag{1}$$

As models with same R_t show very similar line spectra, the main impact of clumping ($D > 1$) is a reduction of the empirically derived mass-loss rates by a factor $\sqrt{D}$. Clumping reduces the electron-scattering wings of strong emission lines. This improves the detailed agreement between calculated and observed line profiles and provides a handle to determine D from spectral fits. Existing analyses concluded $D = 4...10$ being typical for WR stars (Hamann et al. 1998b).

Another recent improvement of the models concerns the inclusion of line-blanketing by iron-group elements (Hillier & Miller 1998, Gräfener et al. in prep.). In contrast to static atmospheres, the expansion causes a frequency coupling by Doppler shifts. This prevents a sampling or re-ordering technique. Instead, all opacities must be treated at their proper frequency. The only approximation concerns the grouping of the energy levels into a small number non-LTE "superlevels".

2. Analyses, problems

Unblanketed "standard" model calculations have been widely applied to Galactic and LMC stars of the WN sequence (e.g. Hamann et al. 1998a). With clumping and iron line blanketing the achieved fit quality is further improved (see Fig. 1 for an example). For WC stars, the agreement between models and observations was not yet satisfactory, and therefore comprehensive spectral analyses are still lacking. The new line-blanketed models will hopefully allow to tackle this task (Hillier & Miller 1999, Gräfener et al. these proceedings).

3. Ionization structure

The stratified ionization structure of Wolf-Rayet atmospheres is directly evident from observational facts. Most WR spectra show lines from more than one ionization stage for the abundant elements (e.g. N III and N IV). Especially the simultaneous appearance of He I and He II is common to almost all WN spectra, with the exception of a few, very hot WN2-3 stars (in the galactic sample, only WR 2, WR 3 and WR 4 have no He I features in their spectra). The lines from

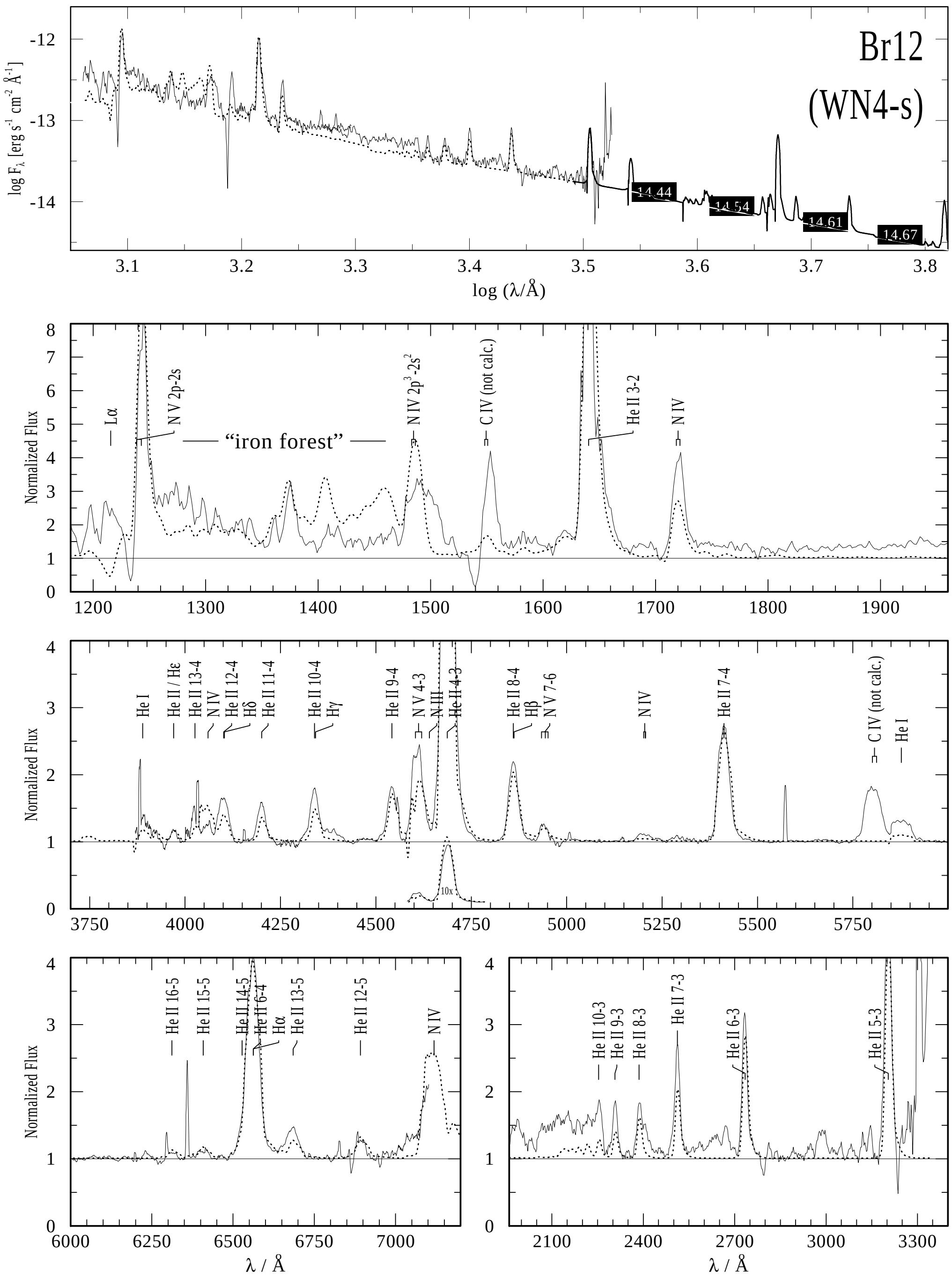

Figure 1. Iron line blanketed WN model (dotted), compared to the observed spectrum of Br 12 (LMC). Model parameters are: $T_* = 100\,\mathrm{kK}$, $\log(L/L_\odot) = 5.35$, $R_* = 1.58\,R_\odot$, $\log(\dot{M}/(M_\odot \mathrm{yr}^{-1})) =$ -4.65, $D = 4$, $v_\infty = 1600\,\mathrm{km/s}$, helium plus $X_\mathrm{N} = 0.008$, $X_\mathrm{Fe} = 0.0004$.

the lowest detectable ion of an element (e.g. He I) often show flat-topped profiles, which indicates that the line is emitted from a hollow sphere of large radius.

The ionization stratification is implicitly modelled by the Non-LTE atmosphere code. In the line-forming layers the radiative ionization processes clearly dominate over collisional ionization. The photons which are energetic enough for a considered ionization process propagate outward through the atmosphere, and when all of them are consumed (absorbed) within some radius from the star the resulting ion is not produced at more distant layers. This resembles the formation of *Strömgren spheres* in a circumstellar medium.

When the hardest photons are consumed by the highest ionization edge, the remaining photons may sustain the next lower ionization process until they are used up as well. The resulting ionization structure thus looks like nested onion shells, with stepwise recombination when proceeding outwards.

This ionization structure can be nicely demonstrated by means of the iron atom, which provides many stages of ionization. Figure 2 shows, for one particular model, the population numbers of the iron ions (number fraction of all heavy particles on a logarithmic scale) as function of the velocity $v(r)$ at the corresponding place in the stellar wind, i.e. the line-forming region is displayed from the static layers ($v = 0$) close to the star, up to large distances where v

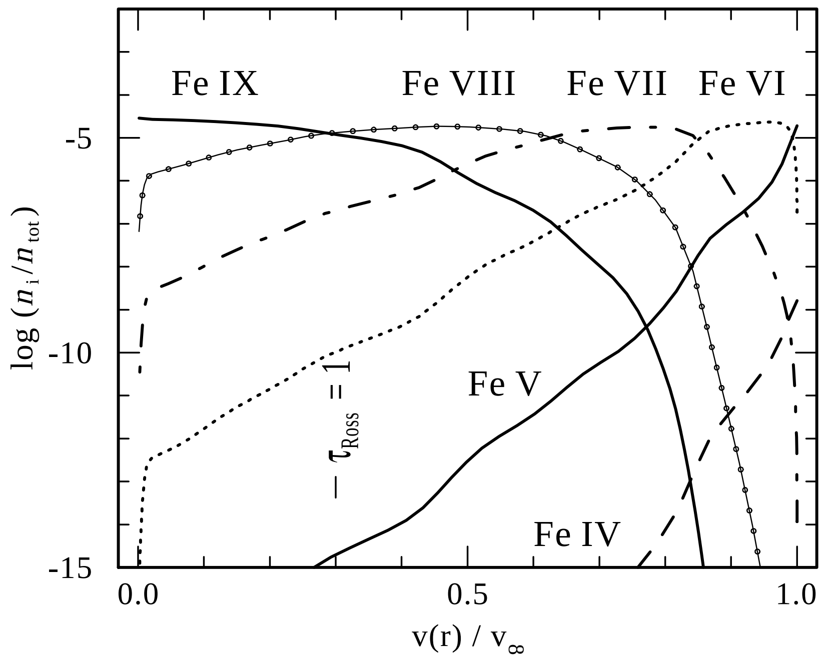

Figure 2. Ionization stratification of iron for a model with $T_* =$ 100 kK and $R_t = 2.5\,R_\odot$. This model fits the spectrum of the early-type WN star Br12 (WN4-s) in the LMC. The relative number occupation of the different ionization stages (labels) are plotted as function of the expansion velocity (in units of the terminal wind velocity) at the corresponding radius. The ionization decreases stepwise from Fe IX to Fe V.

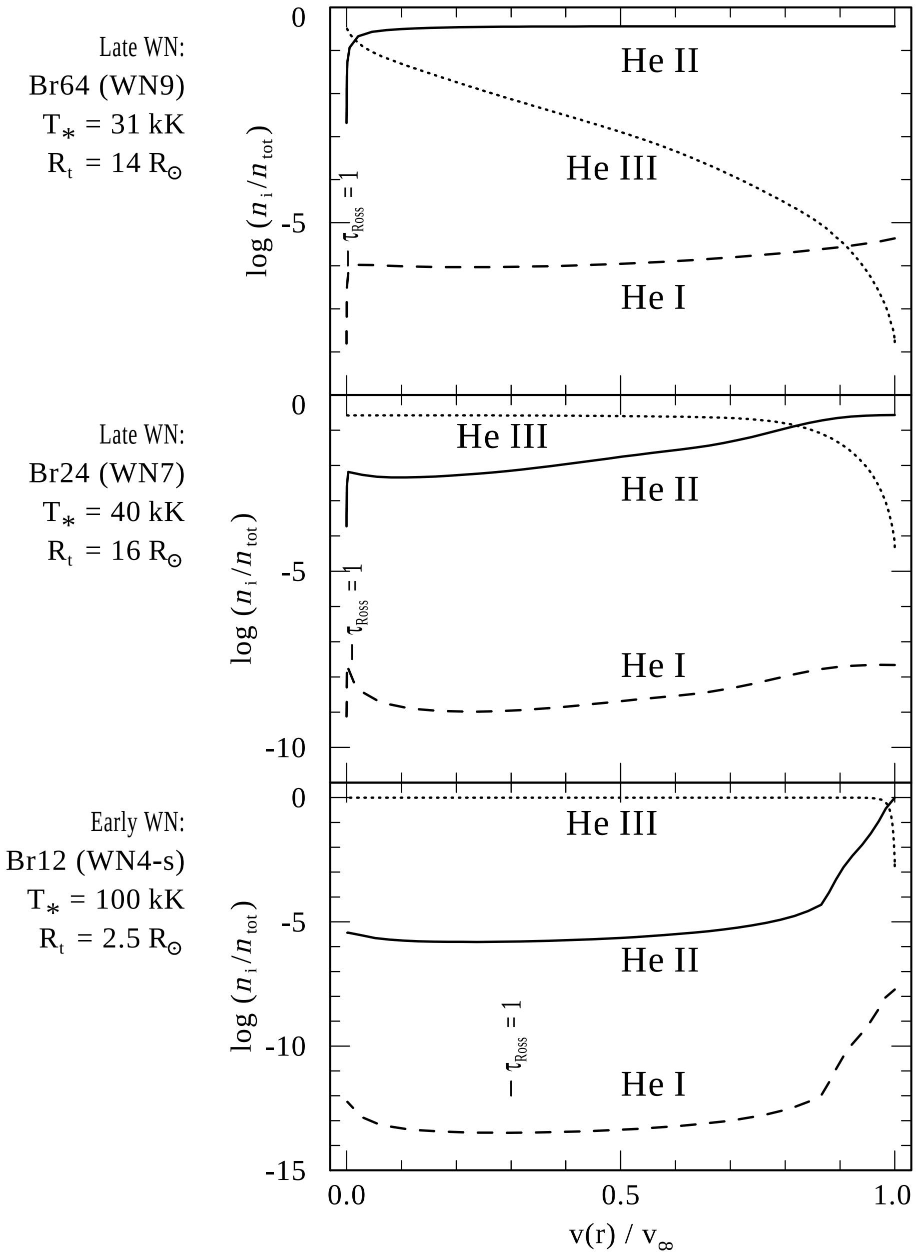

Figure 3. Helium ionization structure in WN models of different spectral subtype. The relative number occupation of the different ionization stages (labels) are plotted as function of the expansion velocity (in units of the terminal wind velocity) at the corresponding radius.

approaches v_∞. The dominant ionization stage changes step by step from Fe IX to Fe V.

This ionization structure of WR atmospheres is quite different from static, plane-parallel LTE atmospheres. In the latter case, Saha's equation rules the

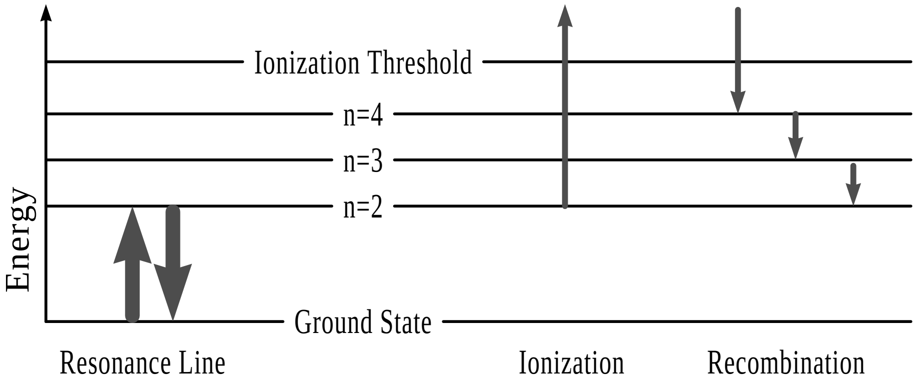

Figure 4. Qualitative sketch of the dominating transition processes in the He II ion. Especially in the cooler WN stars, the strong resonance line supports the population of the $n = 2$ level. Photoionization then preferably occurs from that level, and the recombination cascade feeds the emission lines.

ionization balance, and the exponential density decrease favors *higher* ionization with increasing height.

The definitions of the subtype sequence for WN or WC stars (cf. Smith 1968, Smith et al. 1996), respectively, basically relies on the ratio between lines from different ionization stages. Given the stepwise recombination in typical WR atmospheres, the main difference along the subtype sequence concerns the radius at which the different ions dominate.

This is demonstrated in Fig. 3 for selected models from the WN sequence by means of their helium ionization structure. For the latest subtype (WN9, upper panel) the recombination from He III to He II already occurs close to the photosphere. In the WN7 model (middle panel) helium remains fully ionized until 80% of the terminal velocity is reached. In the WN4-s model (bottom panel) He III dominates up to the terminal velocity.

Note that most emission lines in WR spectra (but not the resonance lines with P-Cygni profiles) are fed by recombination cascades. Thus a specific line is mainly formed in those layers in which the next-higher ionization stage dominates, e.g. He II lines require doubly-ionized helium (He III) while He I lines come from He II dominated layers.

The production of He III by direct photoionization from the He II ground state requires rather energetic photons ($\lambda < 228$ Å). The cooler WR stars take advantage of a special mechanism to facilitate this ionization process: the strong He II resonance line at 303 Å supports a considerable population of the $n = 2$ level, and photoionization then takes place from that level which requires only photons harder than 912 Å (cf. Fig. 4).

4. Wind acceleration

Hydrodynamically consistent models for Wolf-Rayet winds do not exist, and there is an ongoing debate about the driving forces. The "moment ratio"

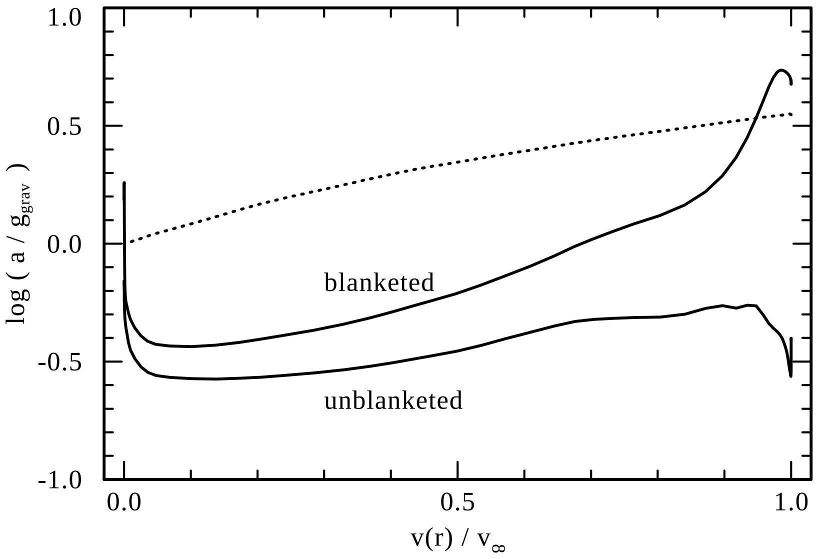

Figure 5. Wind acceleration $a(r)$ in units of the local gravity $g_{\text{grav}}(r)$, as function of the wind velocity $v(r)$ at the corresponding radius r. The dashed curve shows the acceleration which is required to sustain the adopted velocity law, while the full-drawn curves give the radiative acceleration which is provided by the iron-blanketed and unblanketed model, respectively. The model parameters are suitable for the Galactic WN3-w star WR152 ($T_* = 80\,\text{kK}$, $\log(L/L_\odot) = 5.3$, $\log(\dot{M}/(M_\odot \text{yr}^{-1}))$ = -5.6, $D = 4$). The blanketed model fails to produce the required acceleration by only a factor of two.

$\eta = \dot{M} v_\infty c/L$ for WR winds is definitely larger than unity: taking the parameters of the galactic WN sample from Hamann & Koesterke (1998a) and scaling the mass-loss rates down for the effect of clumping (Hamann & Koesterke 1998b), the average values for η are still 4.5, 4.3 and 15 for the WNL, WNE-w and WNE-s spectral subclass, respectively. This is considerably more than the values observed for OB star winds, which can be consistently modelled by the radiation-driven wind theory. However it has been argued (Lucy and Abbott 1993, Springmann 1994) that multiple scattering can lead to moment ratios considerably larger than unity.

Our model atmospheres account for all radiative-transfer effects like multiple scattering and the line-continuum interaction consistently. Iron opacities are included in the blanketed models. As shown in the preceding section, we obtain ionization stratifications with stepwise recombination over many stages, which enhances the radiation pressure as every recombination step provides a "fresh" set of spectral lines which are not yet shaded against the radiation from the photosphere. Thus it is interesting to calculate the radiation pressure from the radiative flux and the opacities as a function of radius. The result is shown in Fig. 5 for one specific model, and compared to the accelerating force which is needed to sustain the adopted mass-loss rate and velocity law. The blanketed model provides much higher radiation pressure than the unblanketed model, due to the iron-line opacities. As expected, the blanketed model is still not hydrodynamically consistent, because we have not constructed the velocity field $v(r)$ from the accelerating force. The remarkable result from Fig. 5 is the rather small discrepancy between requested and available radiative acceleration. A factor of two larger radiation pressure would be able to drive the observed WR wind at any radius.

If we calculate the total work ($\int a\, dr$) done by the radiative acceleration, and divide this by the work (potential and kinetic energy) actually required to drive the wind, we obtain a ratio of 0.50 for the model shown in Fig. 5. Similar numbers were obtained for the WC star WR 111 (Gräfener et al., these proceedings) and for WR 6 (WN5-s). Test calculations showed that choosing a higher clumping parameter D further diminishes the gap between requested and available acceleration.

This discrepancy by only a factor of two can be attributed to the incompleteness of iron line opacities and the neglection of abundant elements like silicon, magnesium and neon. Moreover, WR winds might be initiated by non-radiative forces (e.g. pulsations driven by strange-mode instabilities, Glatzel et al. 1993) which might contribute significantly to the total acceleration. We consider these results as indication that WR winds are accelerated by radiation pressure.

5. Conclusions

Standard models of WR atmospheres can reproduce the observed spectra with growing accuracy. Accounting for clumping in first approximation and the inclusion of iron line blanketing has further improved the achieved agreement and reduced the derived mass-loss rates. The success of the standard model is remarkable, given the strong evidence that WR winds are actually structured and non-stationary. Extensive quantitative analyses of the WC class is still to be done. Forthcoming analyses of WR stars in environments of different metallicity should constrain the evolutionary scenarios. The radiation pressure provided by blanketed models is only a factor of two smaller than required to explain the wind acceleration, following preliminary test calculations. This gives hope that hydrodynamically consistent models of radiation-driven WR winds will become available some day.

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