Colors of the Universe

I've seen things you people wouldn't believe. Attack ships on fire off the shoulder of Orion. I watched C-beams glitter in the dark near the Tannhäuser Gate. All those moments will be lost in time, like tears in rain.

more specifically:

- **Nebulae / emission** (H\(_\text{II}\) regions)
- reminders on microphysics of light emission (prev week)
- ( + some bonus sideways :-) )

**Motivations:**

- Galaxy / veRTIGE collaboration (is small bit)
- emission (ionized) nebulae more beautiful;
  reflection & absorption *nebulae* too ordinary CG :-)

virtual Galaxy exploration ( inside & outside, all scales )
- photo-realistic ( Hubble-like images )
- multispectral (~ Hubble imager, 48 filters, large to peak )
- hard real-time, in highres

Mixes galaxy simulation, astro catalogs, (uncomplete) astrophys + phys knowledge = laws + empirics + data
procedural amplification, GPU voxel rendering (GigaVoxels).

→ H Nebulae was just a very small bit.
Galaxy / veRTIGE project: Results

visible + 656nm + 665nm

far IR  near IR  UV

[ article + video ]
What are nebulae: the big figure

- dark clouds (H+dust)
- spiral gravity waves
- concentrate/collapse
- new stars. Blue giants (O,B)
- UV (ionize,dissolve) +pressure
- bubble phase I,II
- supernova
- phase III: big/super bubbles
visible (RGB) : all pink (boring)

EM spectrum so much richer! (3D vs ∞D)
Filters from IR to UV + bands → peep spectrum in false colors
Eagle
Pillars of creation

→ let now explain all these colors (goal: synthesize nebula)

Raw story:

- (Super)giant blue star (O/B)
  - 15-150 $M_\odot$, 30-50k °K, BB: 10k-10M $I_\odot$
  → UVs Hell
- Gas around (mostly $H_2$) ionized→$H_{II}$
  → ionize↔recombination+photon
  → + other species: spectral lines
Simple figure: homogeneous ionized Hydrogen

Atom; electronic shell $\rightarrow$ de-excited electron + photon
( cf reminders on microphysics of light emission )

 Ionization Energy $\equiv E_{\text{photon}} \leq 91 \text{nm}$
Efficiency: ionization cross section $\sim \frac{1}{\nu^3}$
$\rightarrow$ Star’s UV within 10-40 … 91 nm:
    absorbed into H$_i$ ionization
    rest: pass through

Once ionized, H$_i$ transparent $\rightarrow$ 1st front
But: recombinations ( gas of e$^-$ around H$^+$rate )
    - emit light
    - H to be broken again $\rightarrow$ absorb UV again
    $\rightarrow$ some column of H eats 100% UVs
    $\rightarrow$ Strömgren sphere: $N_{\text{recomb/s}} = \text{flux photons}$
        lum cst, not in $1/r^2$ ! bottleneck = matter, not photons

Other species: ( a lot rarer )
    - can eat weaker star photons; emit different peaks
    - yield different Strömgren radius $\rightarrow$ colored shells
    - depends on Ionization energy: H$_i$: 1312 kJ/mol, S$_i$: 1000 O$_i$: 3388
More realistic figure: spectrum

- H reemit most in UV → reabs → lines not visible ; ~ UV diffusion
- 99% E used to heat e⁻ → de-excitation → spectral series (collisional lines) → 99% E re-emitted as fluorescence, not recombination → Hα, S||, O||… (collisional excitation, forbidden transitions)

\[
H_\alpha = B\alpha_\alpha = 3→2 = \text{pink}
\]

Orion nebula spectrum:
More realistic figure: shape

- Strömgren radius: $H$ assumed uniform, but:

  \[
  \text{proba recombination} = \frac{p_{\text{ion}}}{p_e} \alpha_{n,T} \quad H: \sim \rho^2 : \text{non linear!}
  \]

  \[\rightarrow \text{matter distrib change everything! (denser \rightarrow bright++, opaque++)}\]

  \[\ldots \text{and matter really not homogeneous (prev cloud, bubble, pillars)}\]

  \[\text{NB: loc more linear for other species (} << H \rightarrow e^- \text{ provided by } H) \text{ but correl}\]

  \[\rightarrow \text{not spheres!}\]

  \[\sim \text{topological Strömgren sphere/shells:} \quad \text{(-lin: equiv cone of same } \rho^2(t) \text{)}\]

Sideway: another $\rho^2$ situation: sky (“Rayleigh”) Sideway2: why sky not violet? 4

\[N_2 \text{ molecules… + transients } N_2 \text{ doublets & triplets (} +\ldots\text{)}\]

More realistic figure: misc

- Several OB stars / dust nest + windows / long distance UV (then $1/r^2$)
- species interaction
- super-radiance at border (?) \ldots
- stars creation in pillars / strong O may shuffle protoplanetary disk
- \ldots
More realistic figure: dynamics

Very dynamic picture, ~ front flame:

- **startup**: ionize $\rightarrow$ make transp $\rightarrow$ front go further (up to $R_{\text{Strömgren}}$)

- **Photodissociation**:
  dust grains (+H$_2$, 10K) $\rightarrow$ molecules $\rightarrow$ atoms (+H$_i$) $\rightarrow$ ions (+ H$_{\parallel}$, 10⁵K)
  $\rightarrow$ different lines & opacity
  $\rightarrow$ erodes shell & pillars ("evaporation")

- **High heating + more moles $\rightarrow$ volume** (H: 100 x 2) $\rightarrow$ gas jets (wisps)
- **Pressure $\rightarrow$ pushes front & crushes pillars**

→ Shock wave 20 km/s (>> sound), draw momentum

- **bubble stages**: 1: UV, growth  2: inertia  3: SN explosion (1-10 My)
- **macro picture**: Δ pressures, winds, bubbles foam, super-bubbles…

**Sideway**: our local bubble (Sun pass through)  our local cloud
Wrap-up model (simplified)

[disclaimer: from memory + mix rev. ing. Coherency not guaranteed :-/]

- Shell | at L | \( \Phi(L) = \int_{L}^{L} \rho^2 I^2 \, dl = \alpha I_{\text{star}} \)

- in practice, most \( \rho \) within skin of pillar / propagating shell (phase1)

- Typical markers:
  
  \( O_{\|} \) [mapped blue]: in bubble, stop before pillar / border
  
  \( S_{\|} \) [mapped red]: in fringe, just 1 scatter: silverlining
  
  \( H_{\alpha} \) [pink, mapped green]: bubble + skin + wisps

- procedural \( \rho \) field:
  
  - noise, low in bubble, increasing (highly) from front
  
  - close-form integral \( \Phi(p) \rightarrow \) front location
  
  \[ \rho_{in} + (e^{k_{max}(r-r_{i}, 0)} - 1) \], \( r_{i} = R(t) + \text{noise}(R(t))^n \)

- rendering:
  
  \[ I_{loc} = \alpha I_{\text{star}} \rho^2 \ \Sigma_{i} \text{smooth}_{\text{in}}(\text{range}_{i}, \Phi(p)) C_{i} \]  
  
  (sum shells)

  real-time volume ray-tracing (spectral) + extinction

Sideway: our spectral rendering: Finite Elements → \( I_s, I_{\text{loc}}, T, \) sensor = \( P_{\text{3}(\lambda)e^{\lambda}} \) (closed family)

  just compute up to 5 values per channel
@RSA Cosmos:  
( but not integrated in Sky Explorer: perfs... )

Shadertoys:

shaping noise  [https://www.shadertoy.com/view/lsaSRb]

3D noise + lighting + volume rendering  [https://www.shadertoy.com/view/4sfSz4]

$H\parallel$ region  [https://www.shadertoy.com/view/Md2GWR]

[https://www.shadertoy.com/view/4sjGDR]
Back in context

\[ \text{H}_\text{II} \text{ nebulae were just a small part of the project} \]

if zoom on pink areas + set filters
Sideway: the art of Nasa Hubble Images

- **Scientists choose a filter set** (and look only these outputs)

![Filter set diagram]

& choose pause time

- **Comm scientists prepare images for public:**
  - mapping channels to RGB colors [ std ? ethic ? ]
  - may: gain, contrast, log, substract bg...

**Delusions behind project purpose**

“just simulates Hubble wandering in galaxy”:

- no automatic std mapping to RGB colors
- filter choice depends on target \(\rightarrow\) let operator set from its pedagogical scenario
- pause time hugely differs for stars vs nebulas
- view angle very different dep. on target (zoom vs mosaic)
- sensor PSF (ring+cross around stars) depends on sensor pixel size
  - Zoom ≠ get closer ≠ wide angle

  ![PSF image]

- astrophysics / astronomic data far from complete, not always consensus
- dialog with physicists not always easy (cultural gaps, even between them)

**Some side messages:**

→ think longer about “does the question makes sense”
  
or “what is *exactly* the request (or concept)” “si c’est flou, ya un loup” :-p

question the full real pipe-line (not isolated scientific end-concept)

→ CG as an integrative + re-modeling science
  
  + stochastic extrapolation: instantiating high-res fields obeying global prop.
Popularization article & video on whole Galaxy / veRTIGE project

Highres part: ( not fast enough for integration )

hard real-time: integrated in Sky Explorer