

LA SPECTROSCOPIE

LES SECRETS DE LA LUMIERE



AUGUSTE COMTE 1857

On peut imaginer déterminer la forme des étoiles, leurs distances, leurs tailles et leurs mouvements, mais il n'y a aucun moyen envisageable qui nous permettrait un jour de déterminer leur composition chimique, leur structure minéralogique ou la nature des organismes vivants qui vivent à leur surfaces.

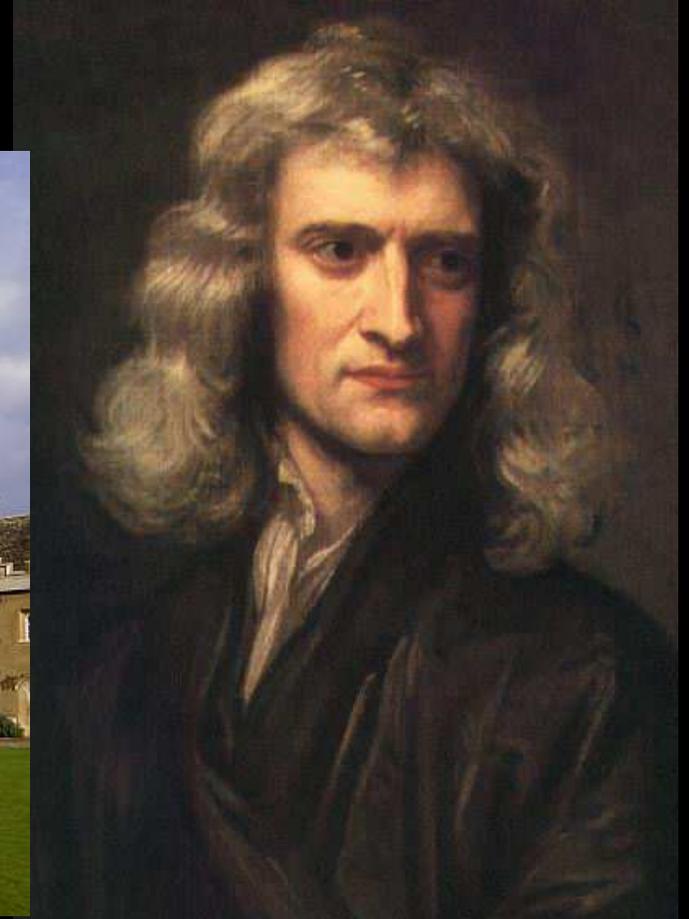
Nos connaissances concernant les étoiles sont nécessairement limitées à leur comportement géométrique et mécanique.

AUGUSTE COMTE

Cours de philosophie positive (1830)



1666 ISAAC NEWTON, ALORS ETUDIANT A L'UNIVERSITE
DE CAMBRIDGE AU TRINITY COLLEGE

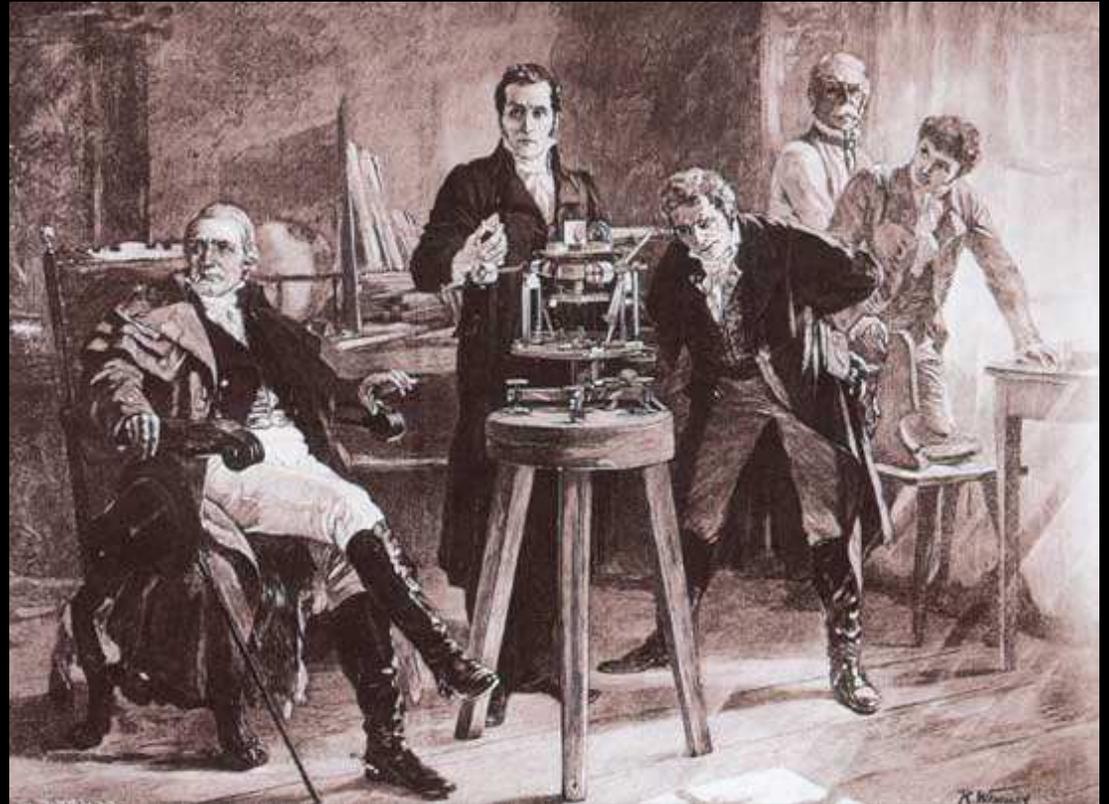
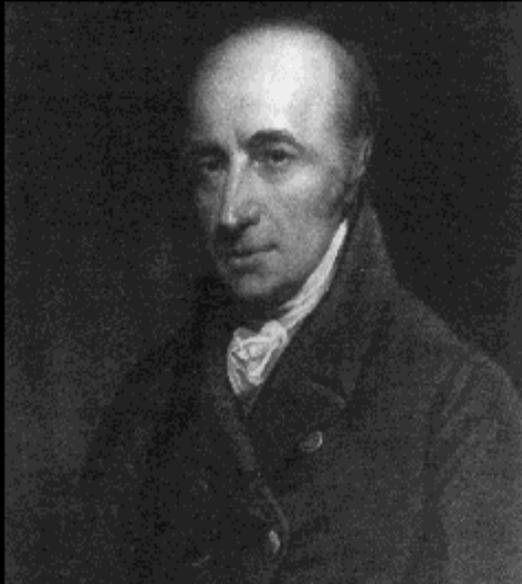
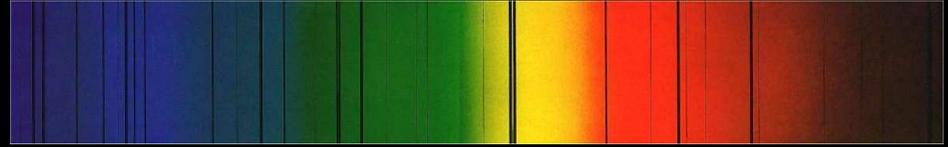


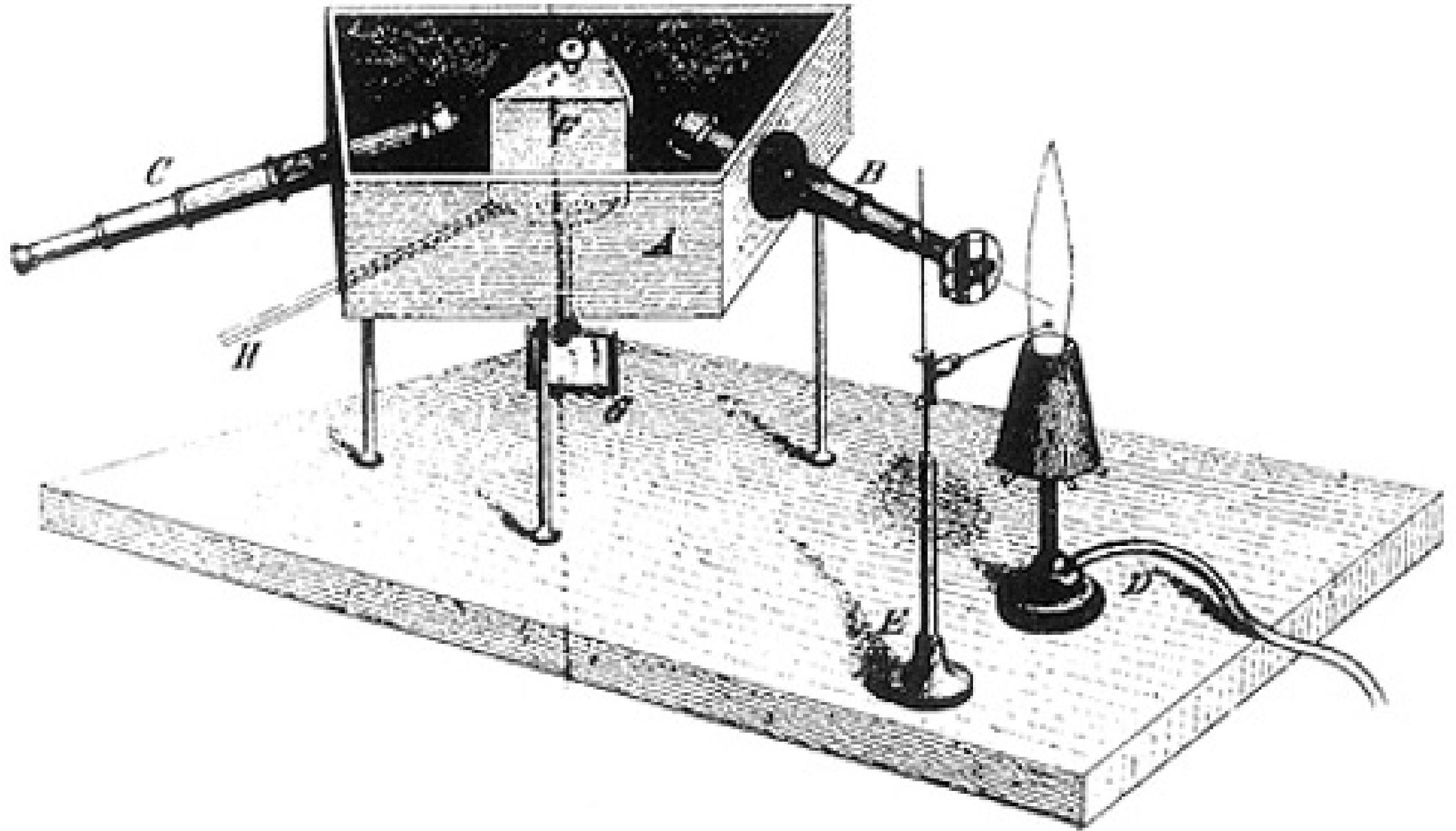
TRINITY COLLEGE

1666 ISAAC NEWTON DECOUVRE LE SPECTRE DE LA LUMIERE BLANCHE

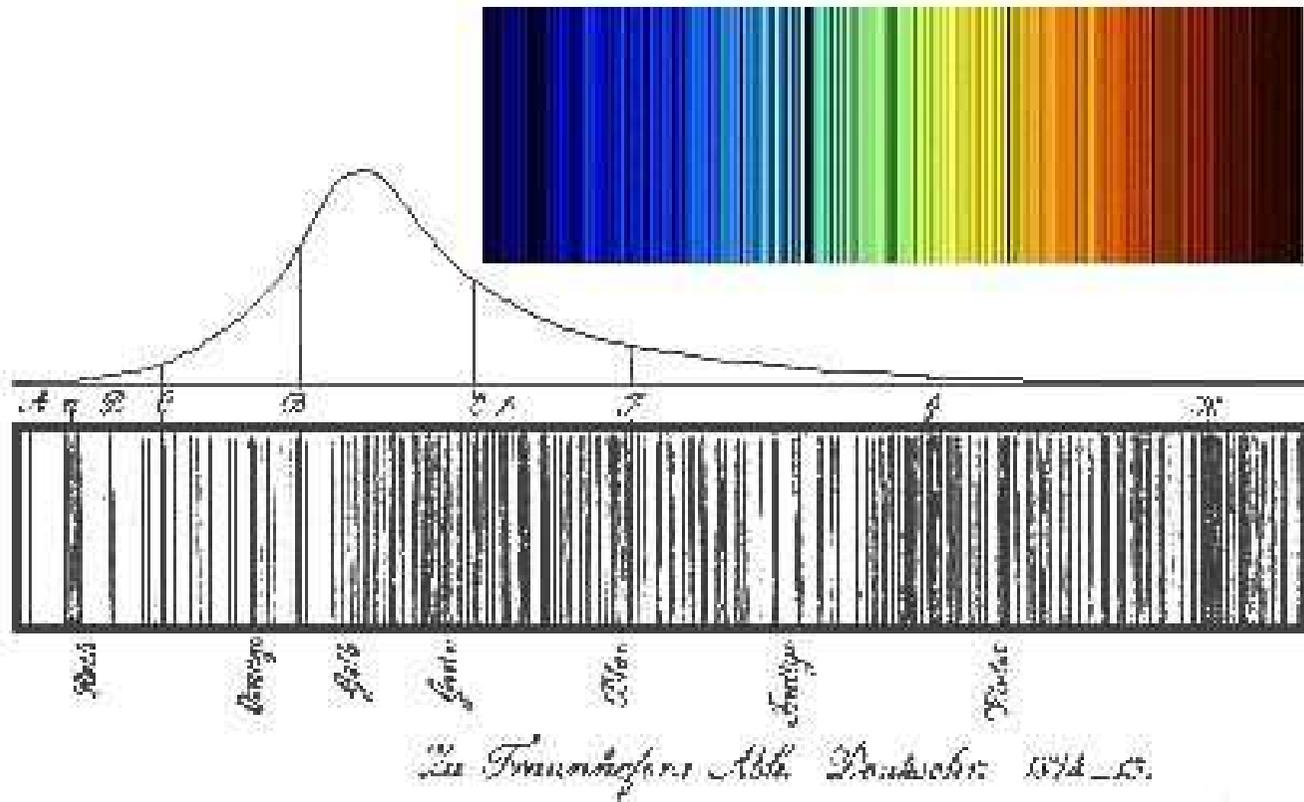


1802 WILLIAM WOLLASTON DECOUVRE 7 RAIES SOMBRES DANS LE SOLEIL

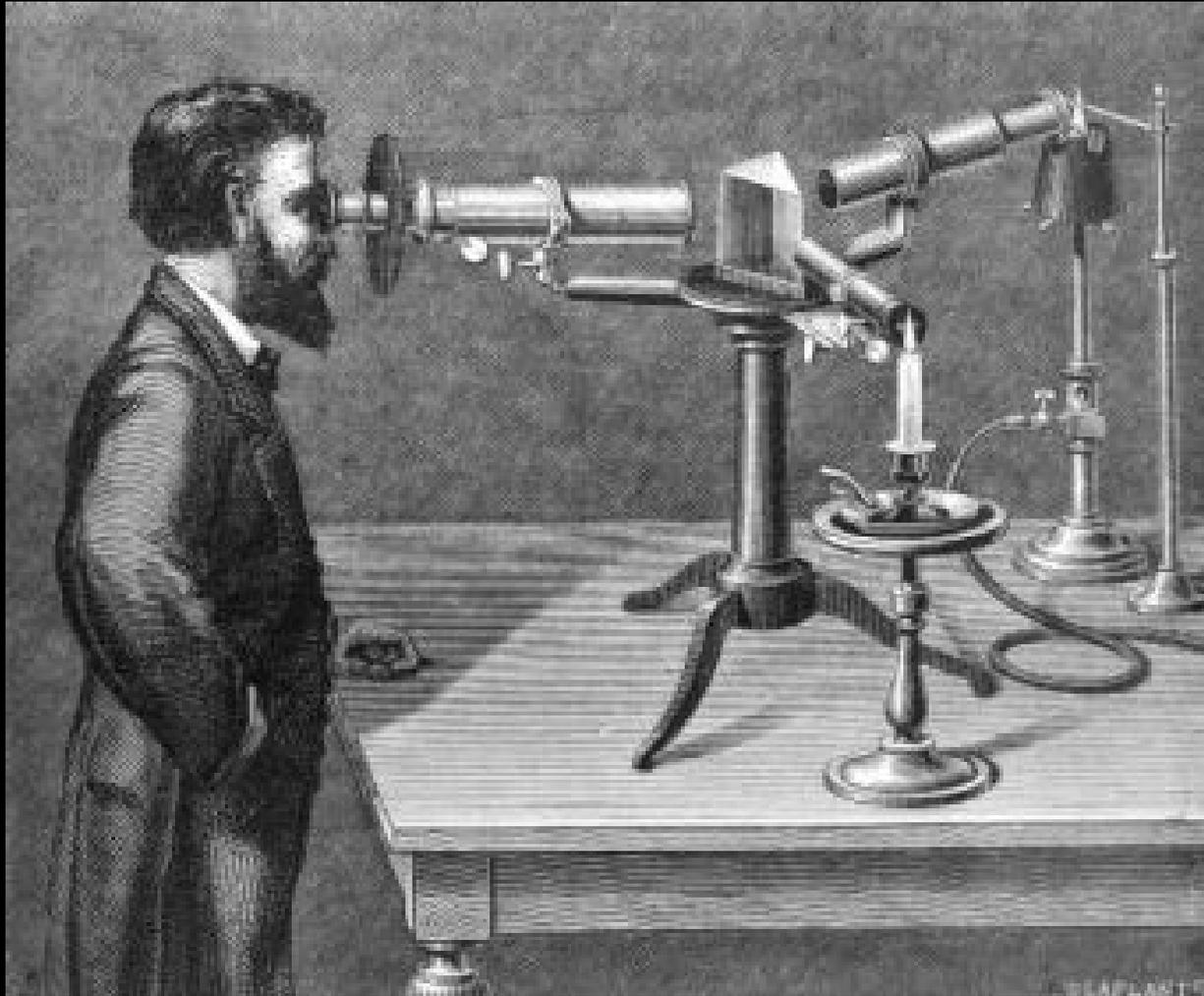




1814 JOSEPH FRAUNHOFER DECOUVRE 500 RAIES DANS LE SOLEIL

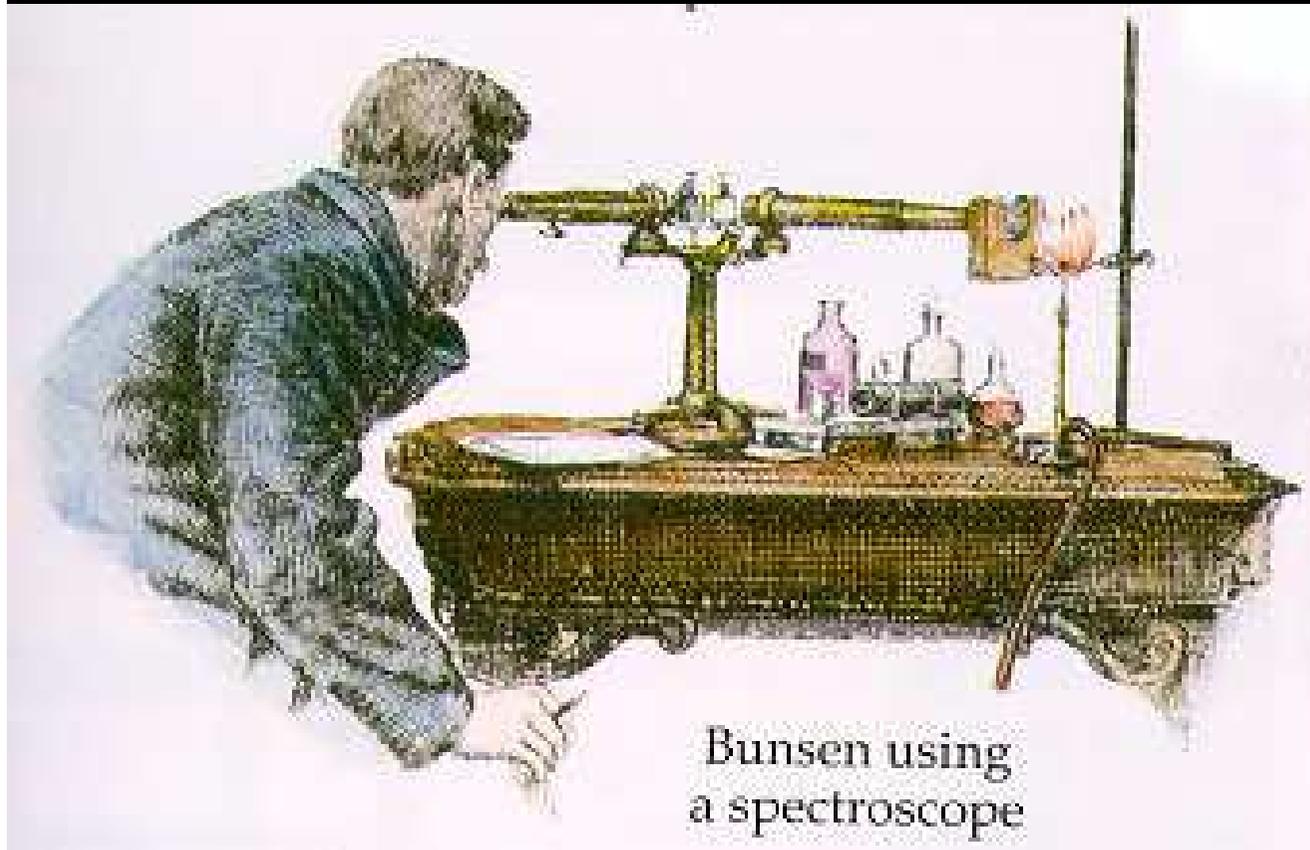


1859 WILHEM BUNSEN ET GUSTAV KIRCHHOFF INVENTENT L'ANALYSE SPECTRALE

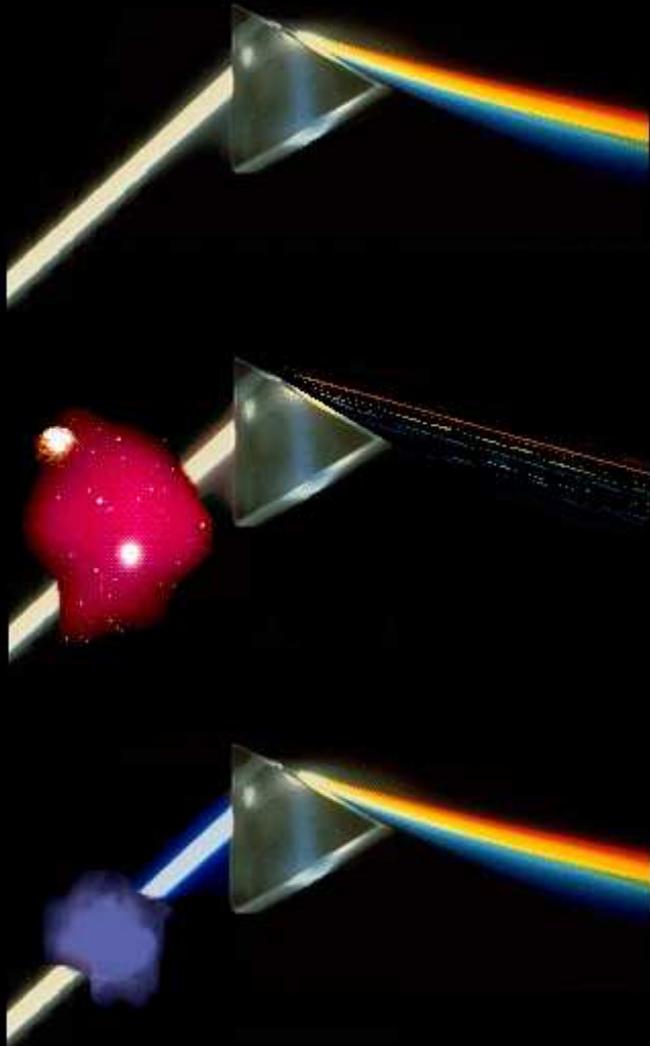


LE SPECTROSCOPE EST UN INSTRUMENT SIMPLE

Cet appareil se compose principalement d'un prisme pour disperser la lumière émise par une source, d'une lentille télescopique pour observer les détails du spectre.



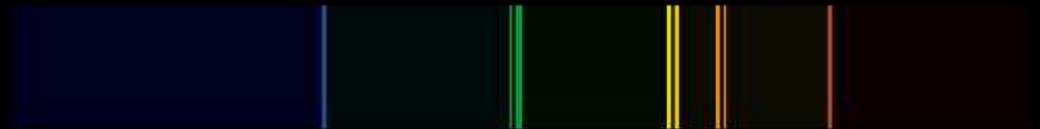
LOIS DE KIRCHOFF



Spectre continu



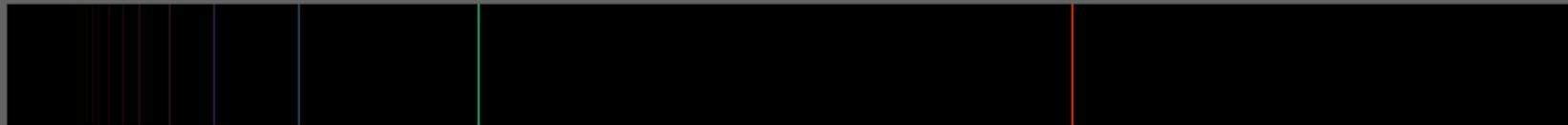
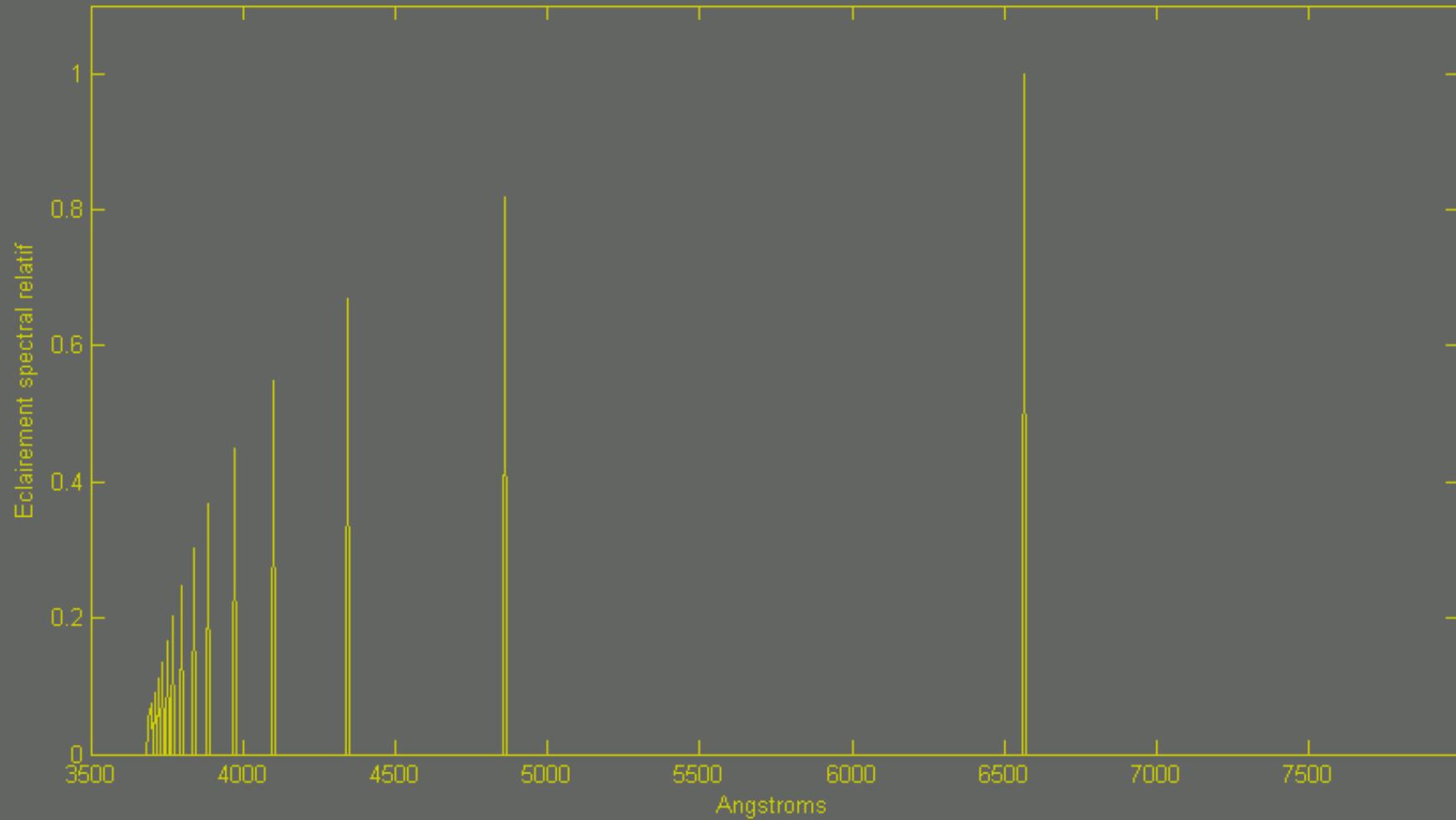
Spectre d'émission



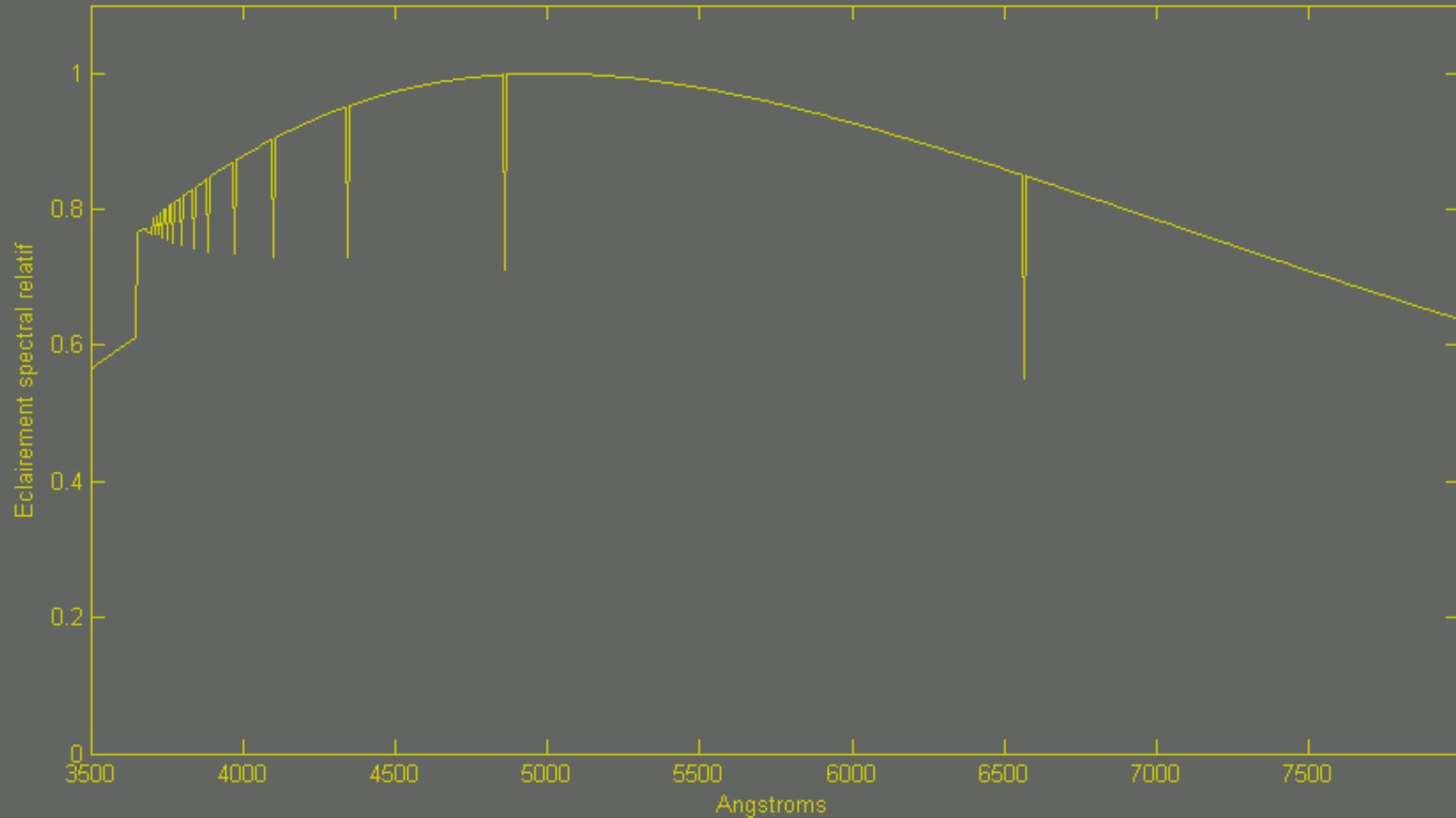
Spectre d'absorption



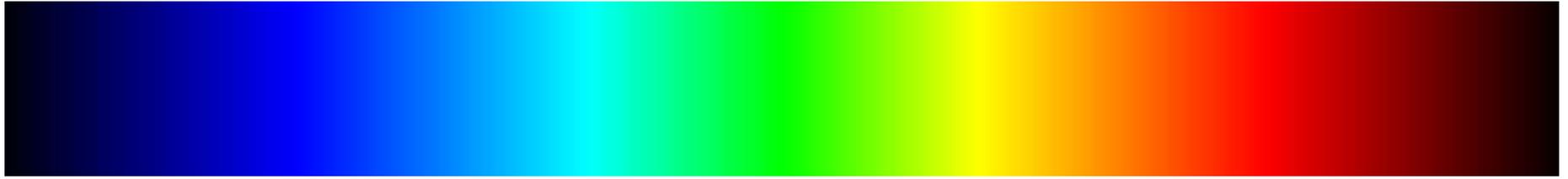
Spectre de l'Hydrogène en émission



Spectre de l'Hydrogène en absorption



Continuum



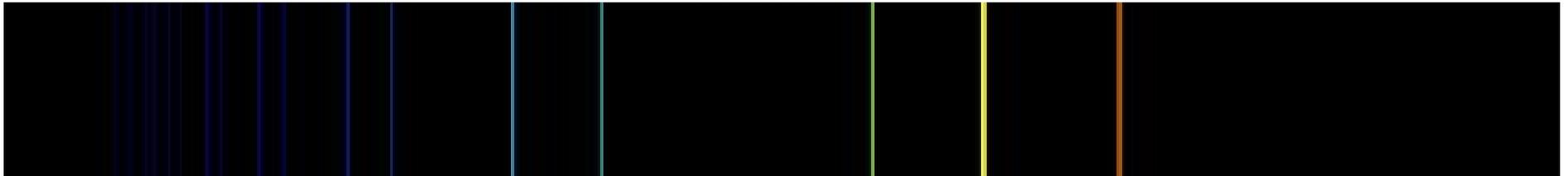
Hydrogène



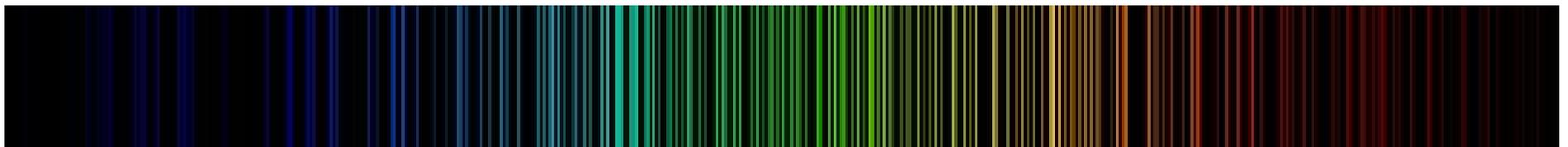
Hélium



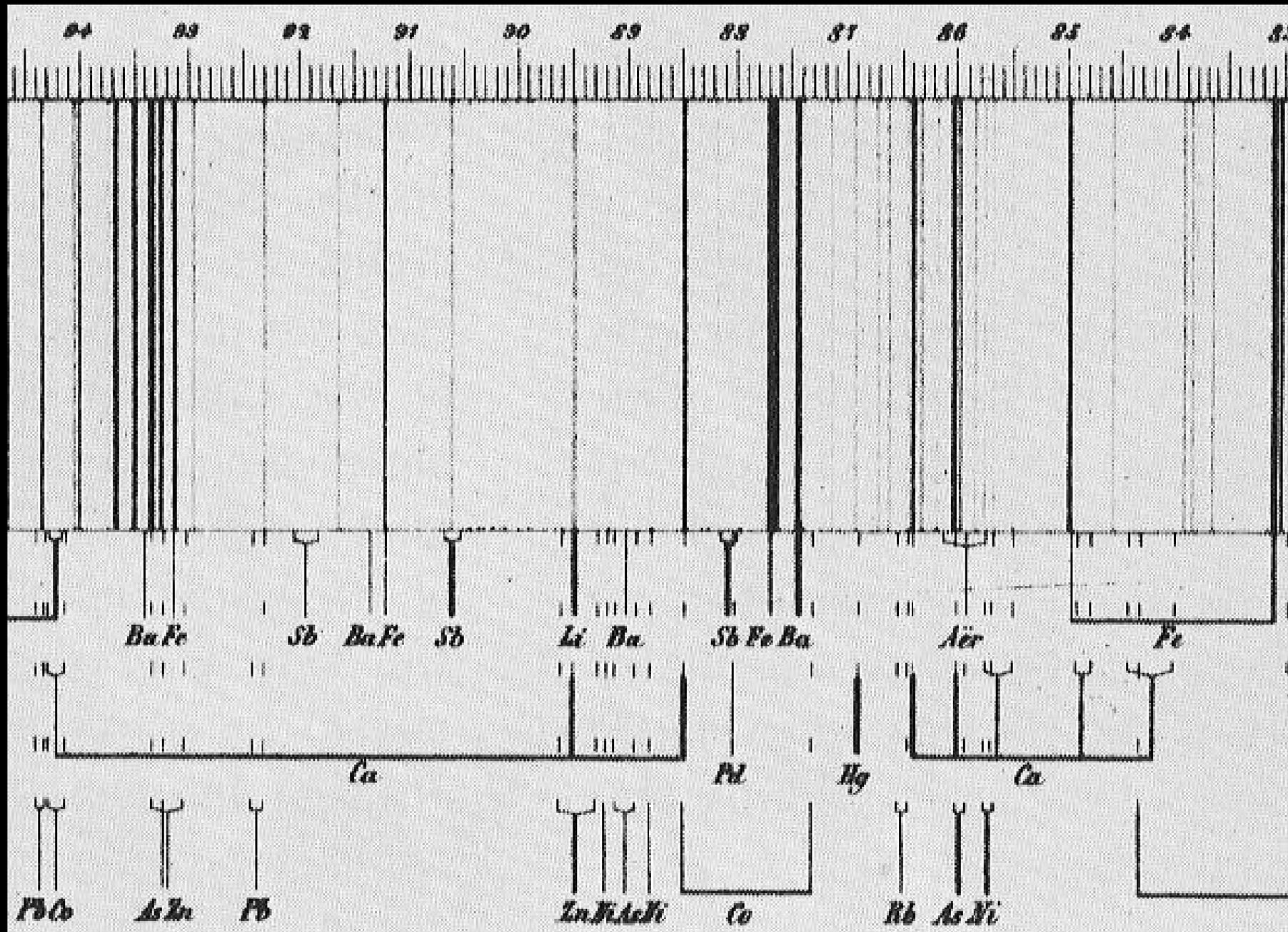
Sodium



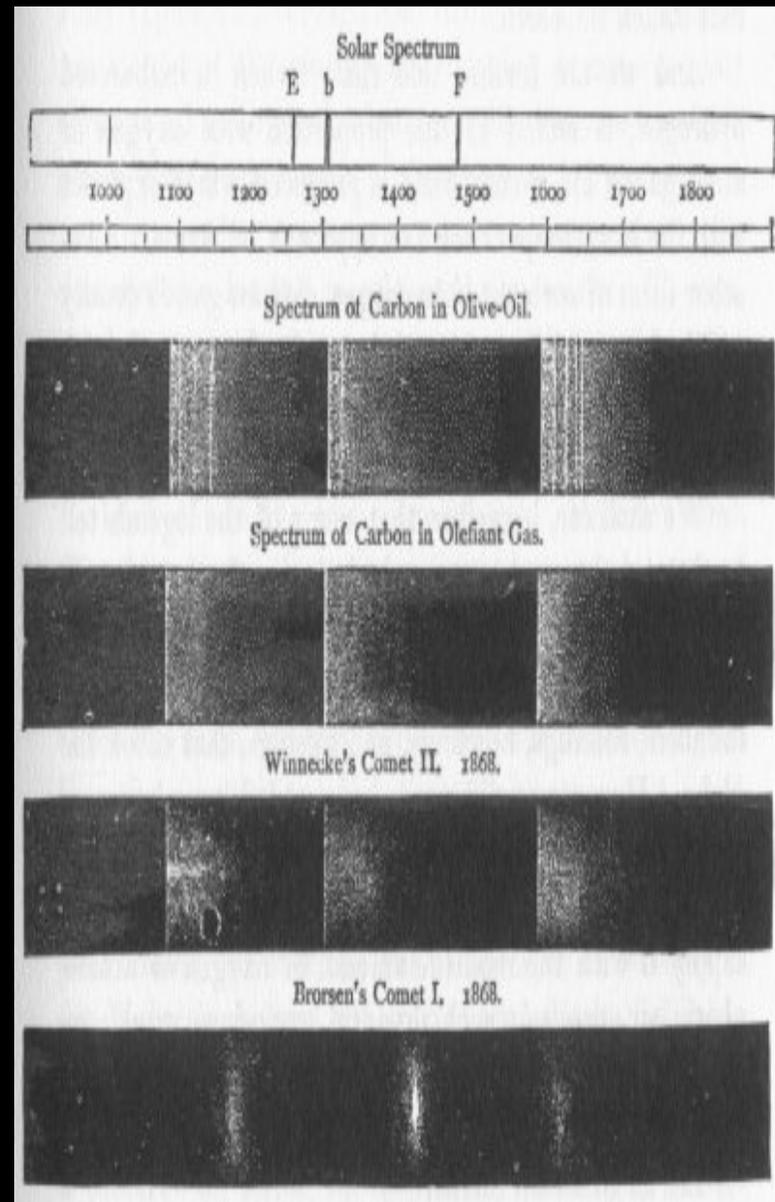
Argon



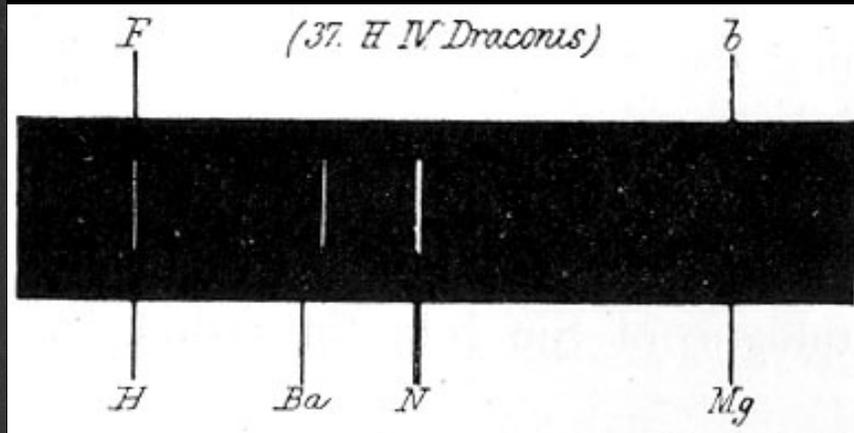
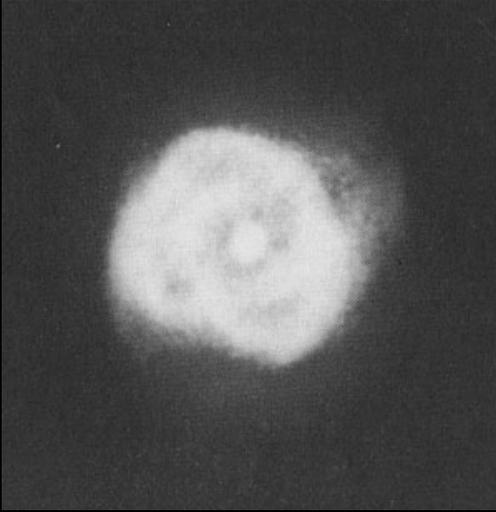
Détail du Spectre solaire par Kirchhoff en 1863



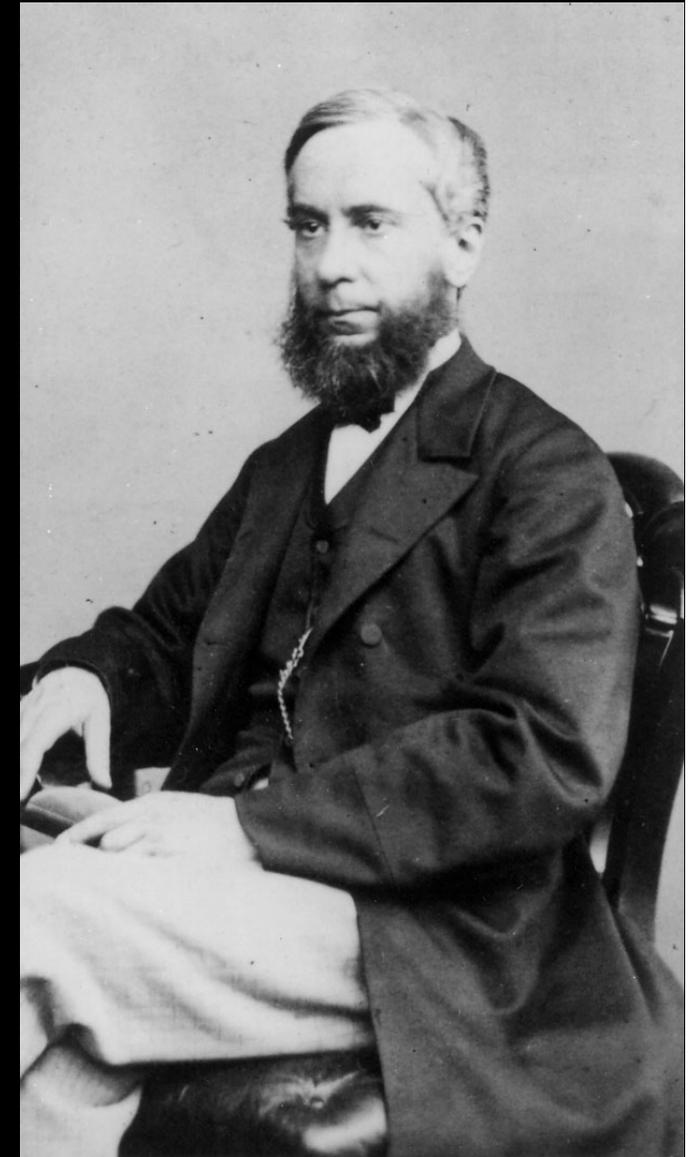
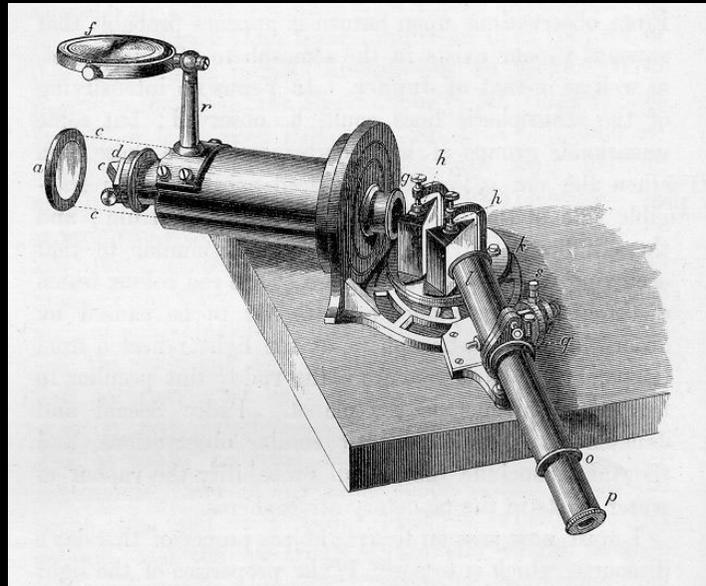
1864 GIOVANNI DONATI DECOUVRE DES RAIES BRILLANTES DANS LES COMETES



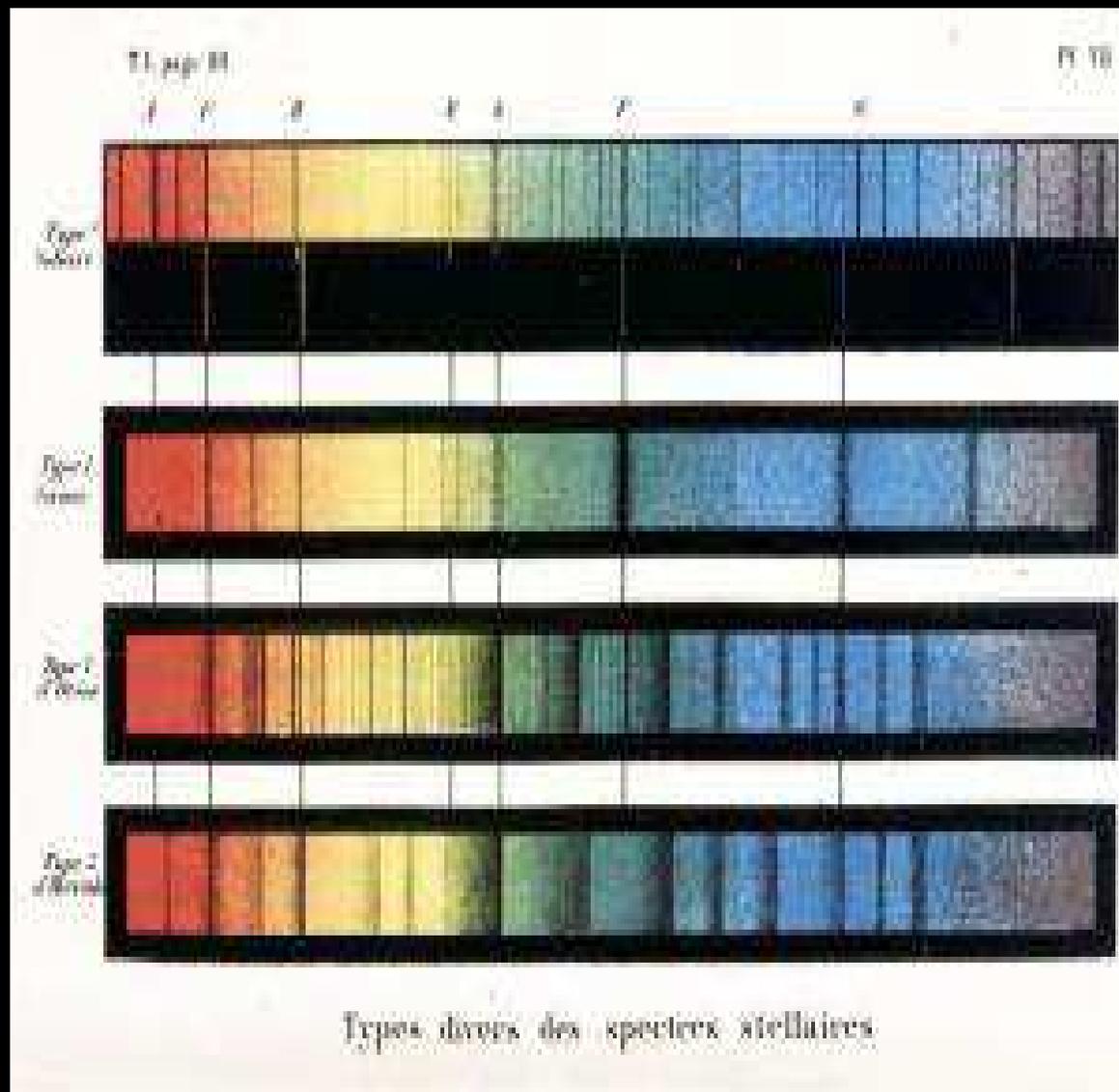
1868 WILLIAM HUGGINS ETUDIE LE SPECTRE DES NEBULEUSES



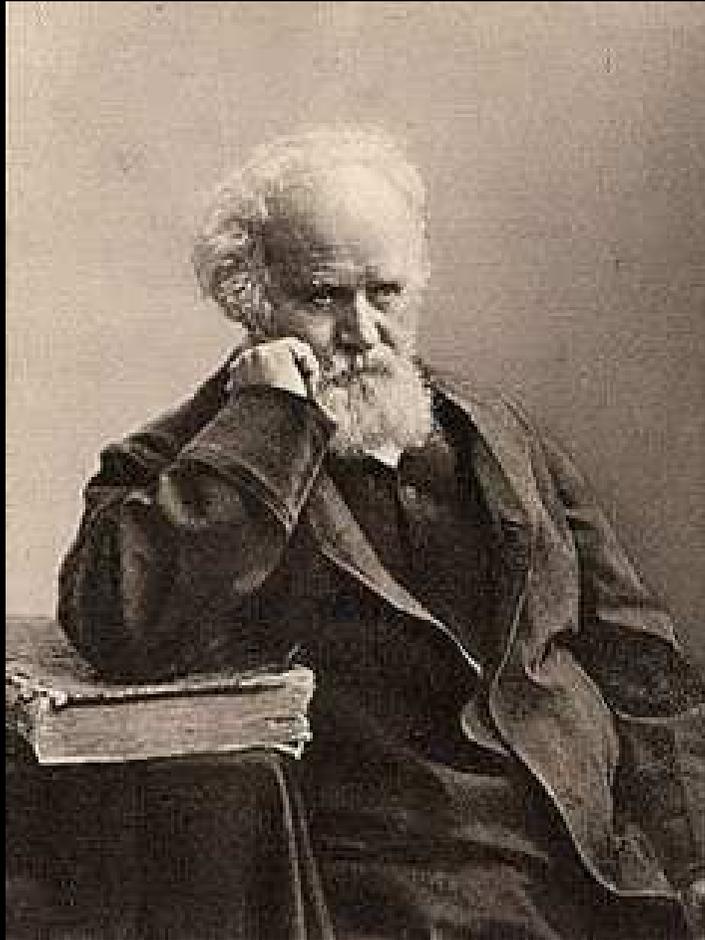
« Pas un spectre comme d'habitude, seulement quelques raies lumineuses, cette nébuleuse n'est pas une accumulation d'étoiles mais un nuage de gaz lumineux »



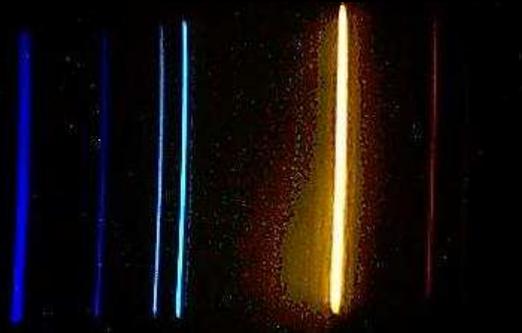
1868 ANGELO SECCHI PRODUIT UNE CLASSIFICATION SPECTRALE EN 4 CATEGORIES



1868 JULES JANSSEN ET NORMAN LOCKYER DECOUVRENT
L'HELIUM DANS LE SPECTRE SOLAIRE LORS D'UNE ECLIPSE
TOTALE EN INDE

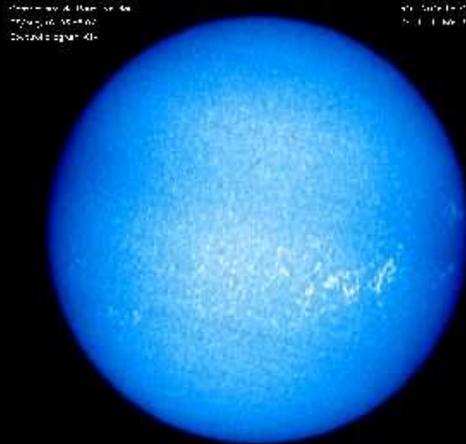


JULES JANSSEN

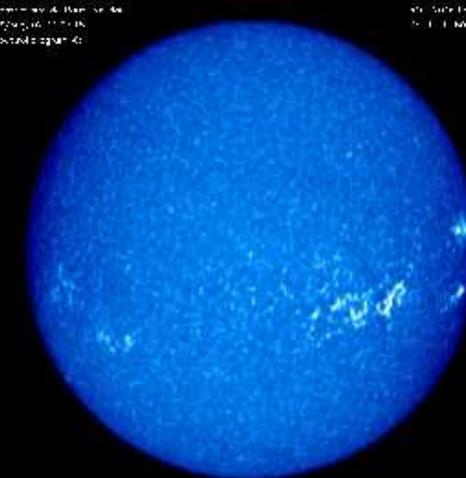
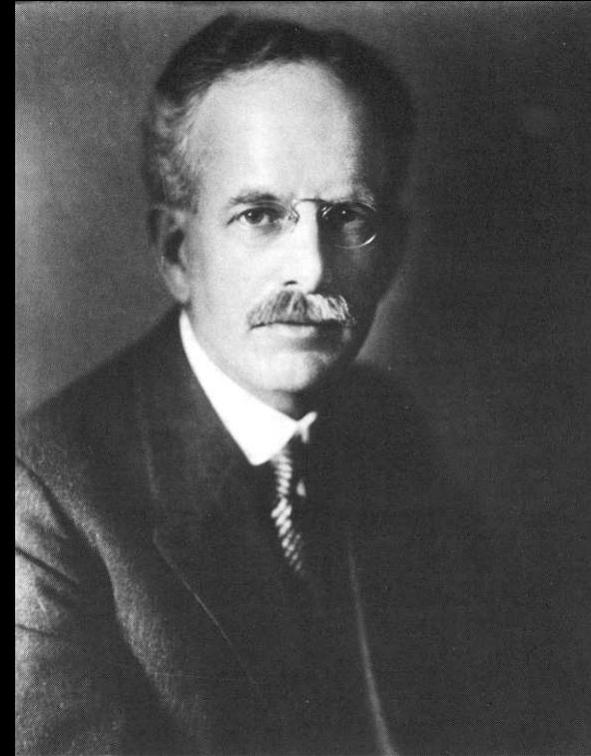


NORMAN LOCKYER

1892 Henri Deslandres et Georges E. Hale



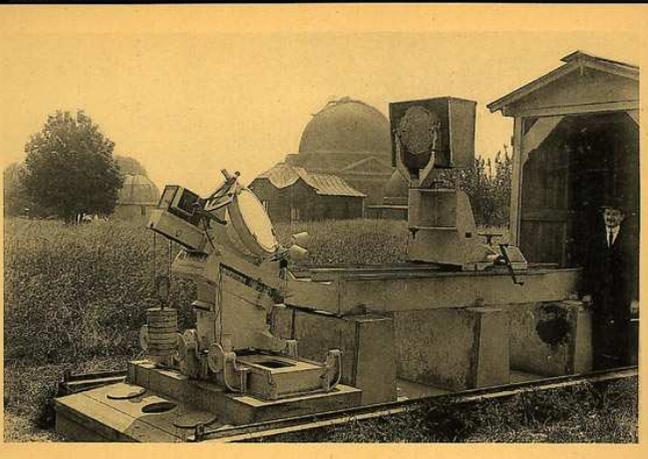
CaK1v 2006-08-02/06:58:07 UT



CaK3 2006-08-02/11:07:15 UT

4 bis - COELOSTAT A DEUX MIROIRS ASSOCIE AU SPECTROHELIOGRAPHE. VU DU NORD-OUEST.

Photo: Baldet

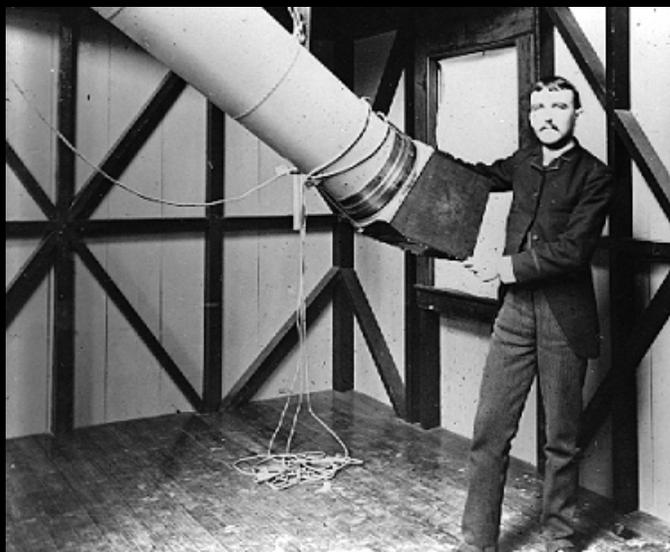
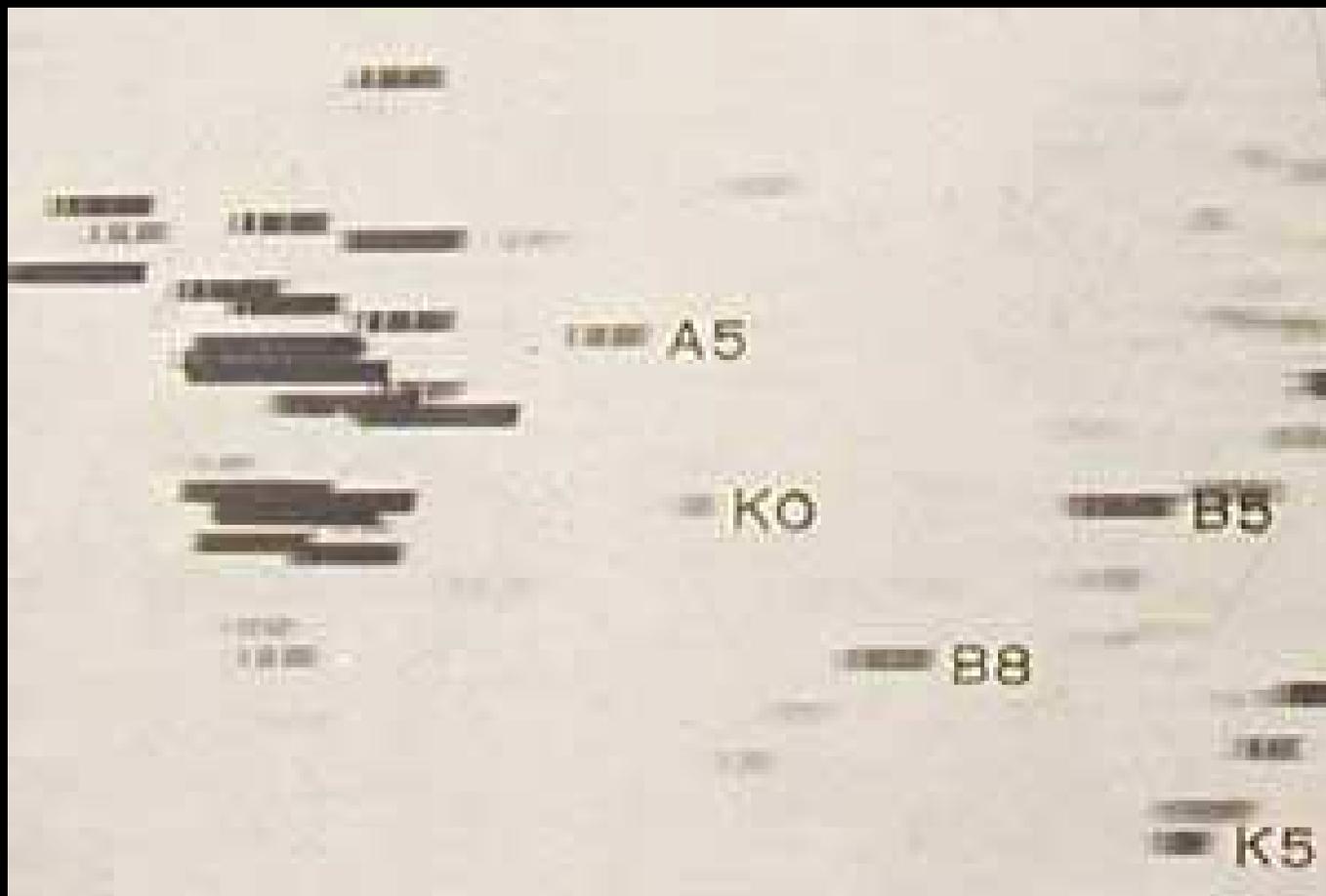


10 - SPECTROHELIOGRAPHE QUADRUPLE DE 15^m

Photo: Pasteur

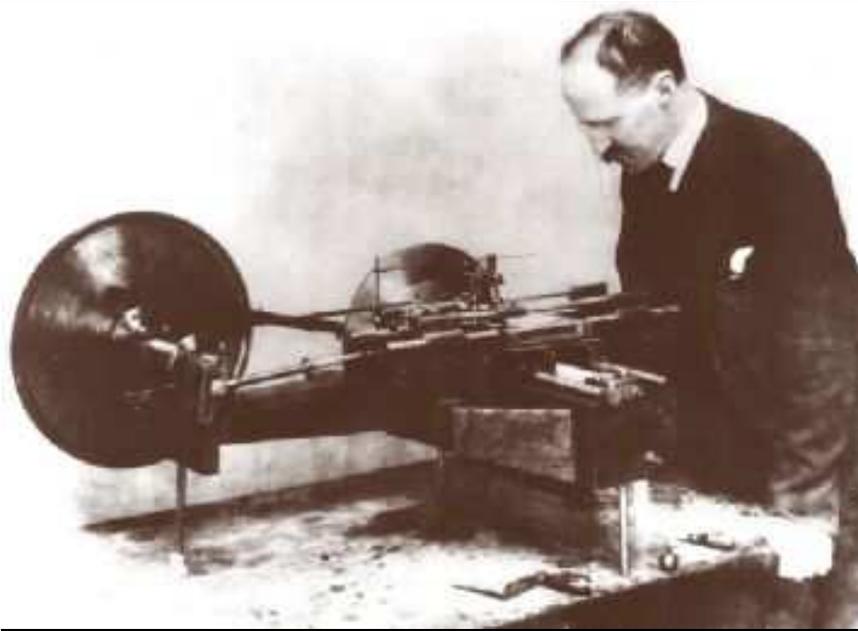


1872 HENRY DRAPER PHOTOGRAPHIE LES PREMIERS SPECTRES STELLAIRES



Henry Draper (1837-1882) SI neg. 48,235

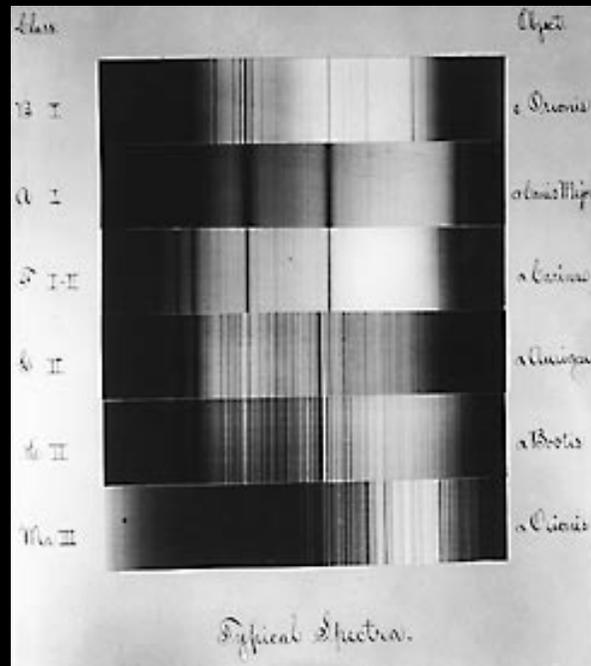
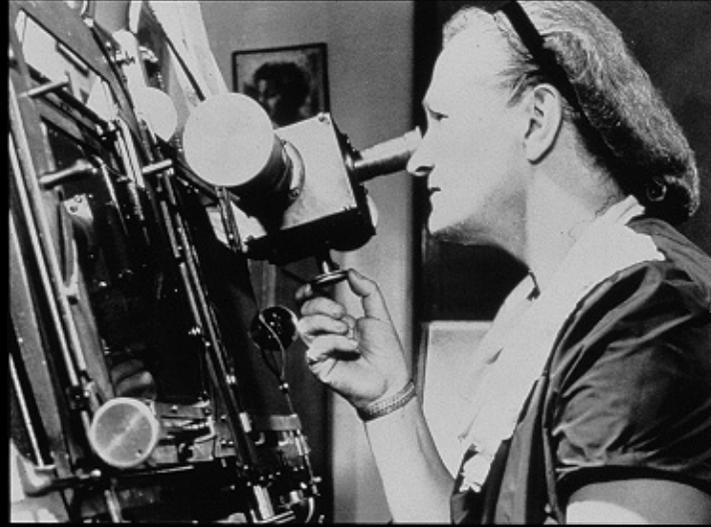
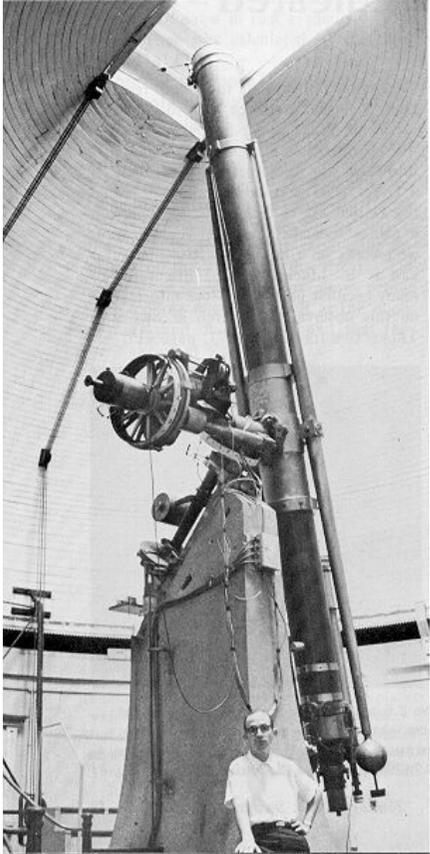
1895 HENRY ROWLAND CONSTRUIT DES RESEAUX DE
DIFFRACTION LUI PERMETTANT D'ENREGISTRER 20000 RAIES
DANS LE SOLEIL



L'EQUIPE D'ASTRONOMIE FEMININE DE L'UNIVERSITE D'HARVARD EN 1918



1915 ANNIE JUMP CANNON CLASSE 350000 ETOILES ET DIVISE LES ETOILES EN CLASSE SPECTRALE O,B,A,F,G,K,M



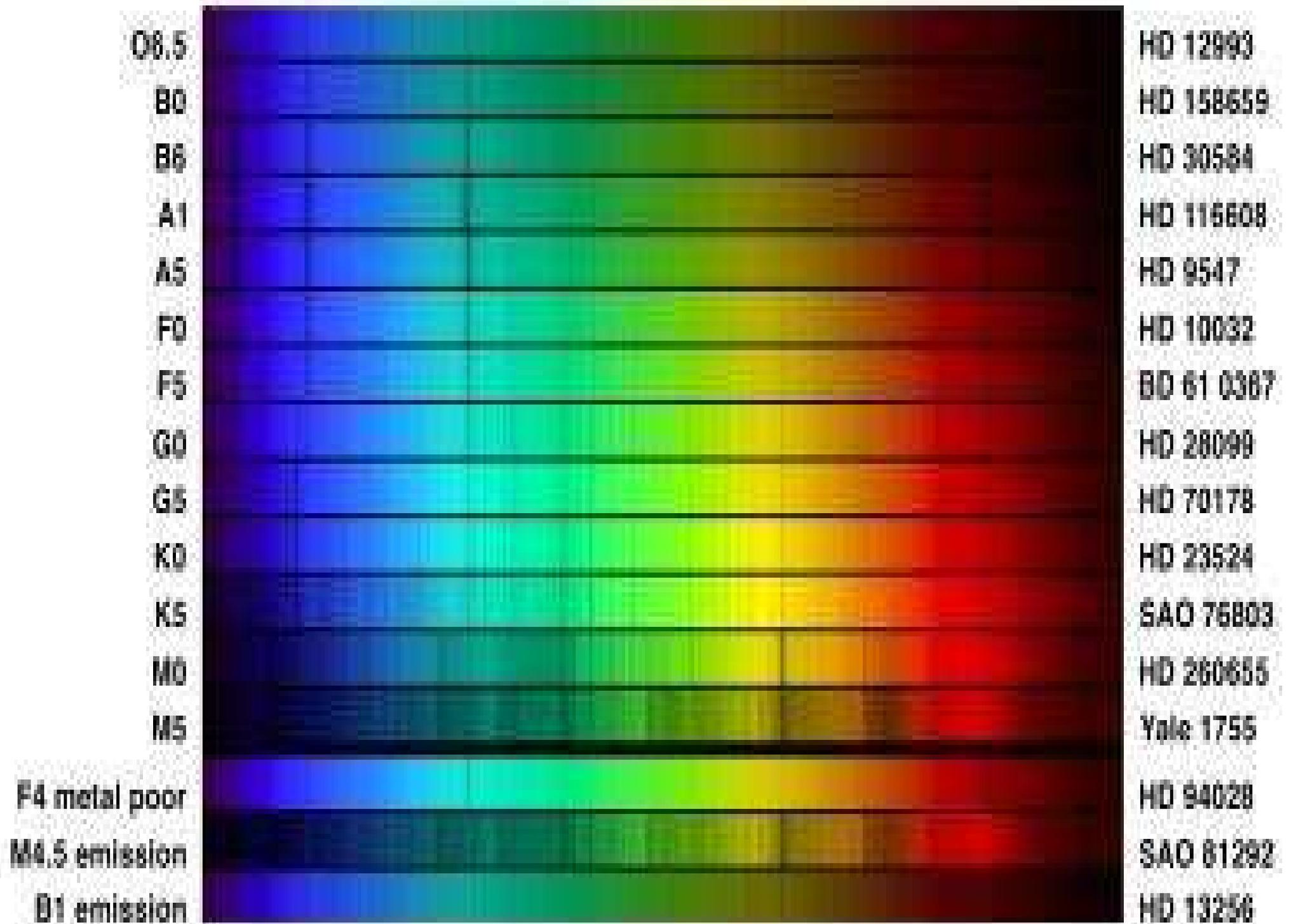
Spectral Type	Characteristics
O	Hottest blue-white stars with few lines. Strong He II absorption (sometimes emission) lines. He I absorption lines becoming stronger.
B	Hot blue-white stars. He I absorption lines strongest at B2. H I (Balmer) absorption lines becoming stronger.
A	White stars. Balmer absorption lines strongest at A0, becoming weaker later. Ca II absorption lines becoming stronger.
F	Yellow-white stars. Ca II lines continue to strengthen as Balmer lines continue to weaken. Neutral metal absorption lines (Fe I, Cr I).
G	Yellow stars. Solar-type spectra. Ca II lines continue becoming stronger. Fe I, other neutral metal lines becoming stronger.
K	Cool orange stars. Ca II H and K lines strongest at K0, becoming weaker later. Spectra dominated by metal absorption lines.
M	Coollest red stars. Spectra dominated by molecular absorption bands, especially titanium oxide (TiO). Neutral metal absorption lines remain strong.

Table 8.1 Harvard Spectral Classification.

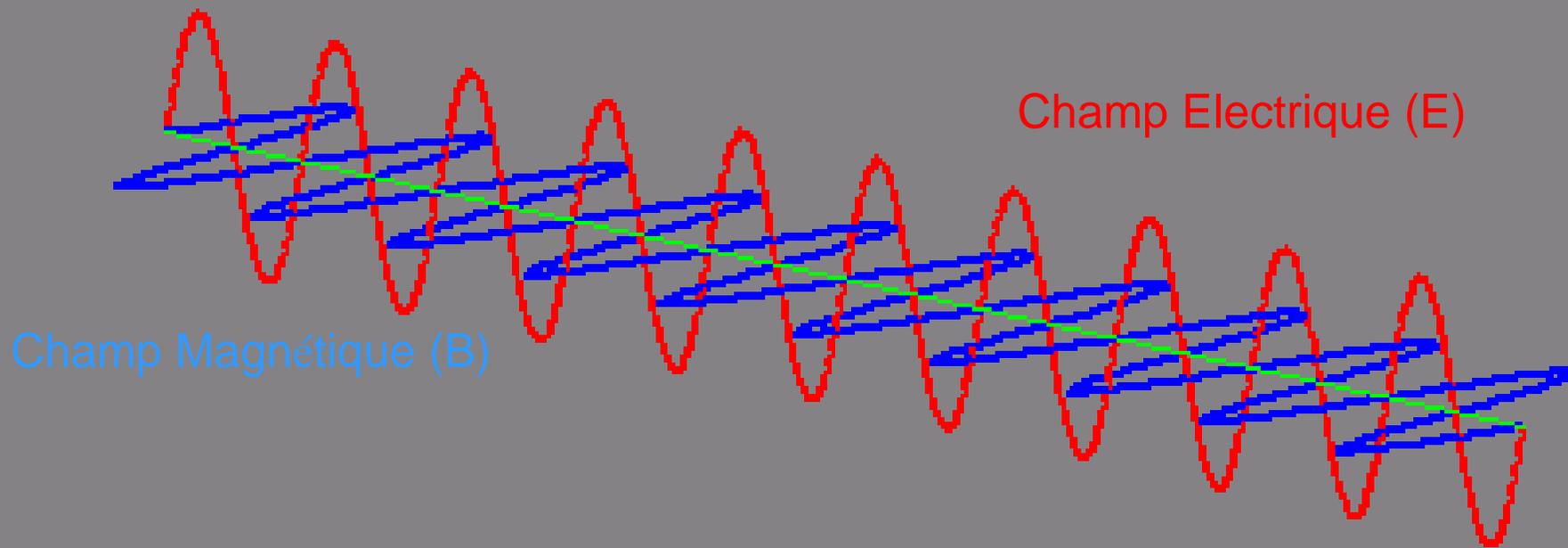
Main-Sequence Stellar Properties by Spectral Class

Spectral Class	Typical Surface Temperature (K)	Color	Mass* (M_{\odot})	Luminosity* (L_{\odot})	Lifetime* (10^8 yr)	Familiar Examples
O	>30,000	Electric Blue	>20	>100,000	<2	
B	20,000	Blue	8	3000	10	Spica (B1)
A	10,000	White	3	75	400	Vega (A0) Sirius (A1)
F	7,000	Yellow-white	1.5	4	4000	Procyon (F5)
G	6,000	Yellow	1.0	1.5	9000	Sun (G2) Alpha Centauri (G2)
K	4,000	Orange	0.5	0.1	60,000	Epsilon Eridani (K2)
M	3,000	Red	0.1	0.005	200,000	Proxima Centauri (M5) Barnard's Star (M5)

* Approximate values for stars of solar composition

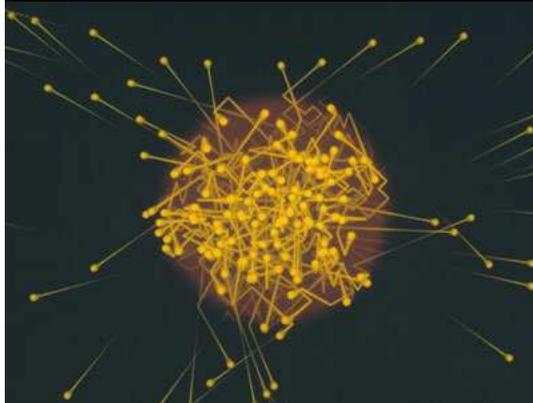
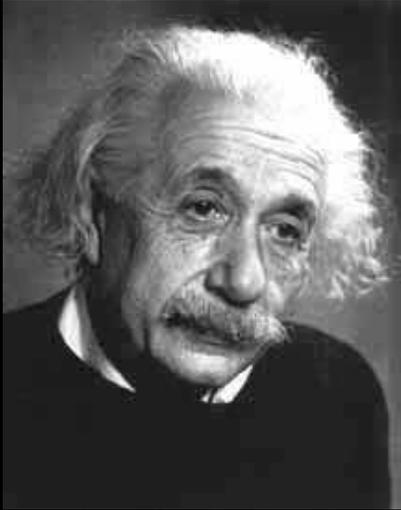


L'onde Electromagnétique



célérité
 $c = 300000 \text{ Km/s}$

LA LUMIERE UNE ONDE ET UN CORPUSCULE

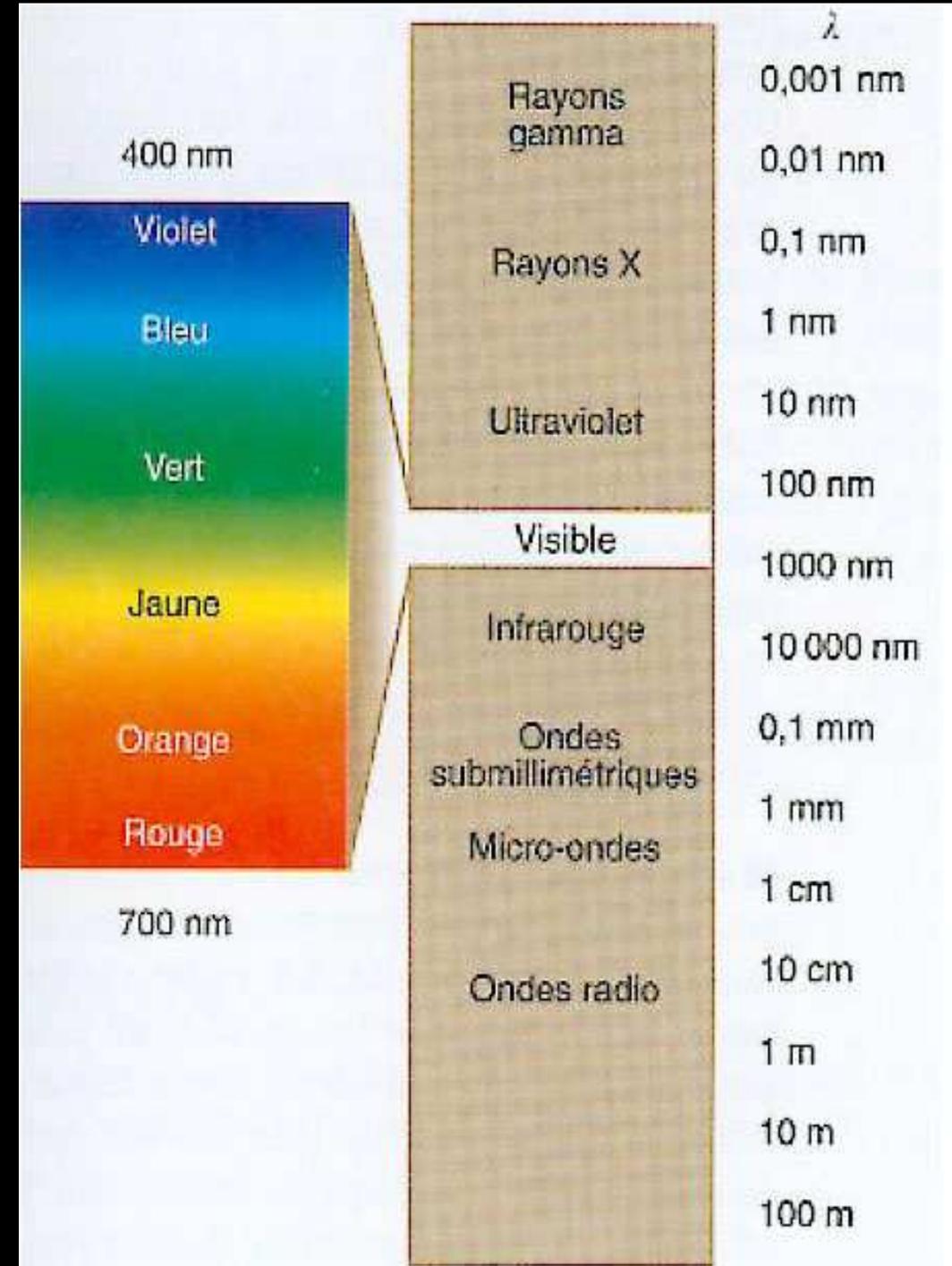


ALBERT EINSTEIN

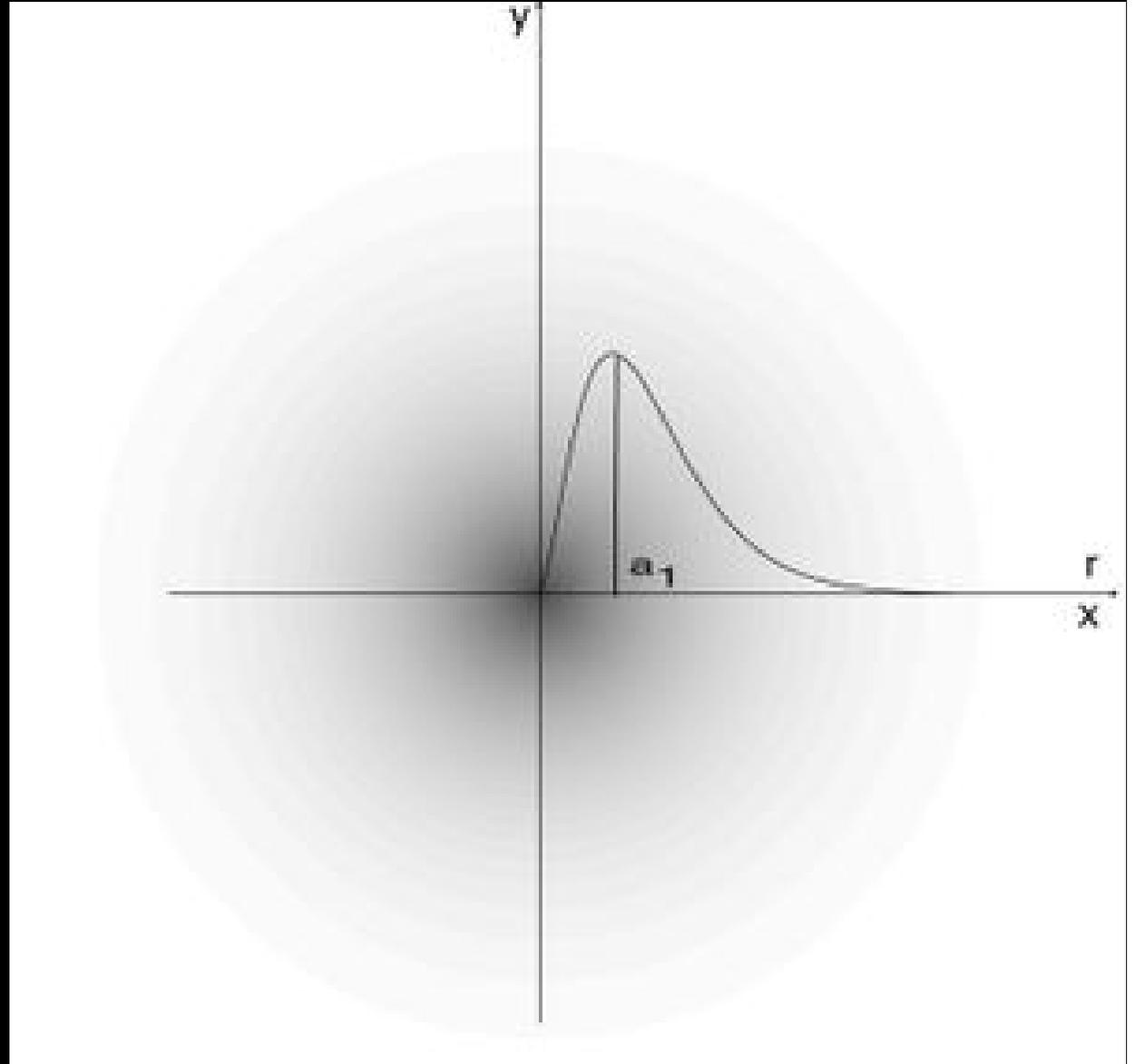
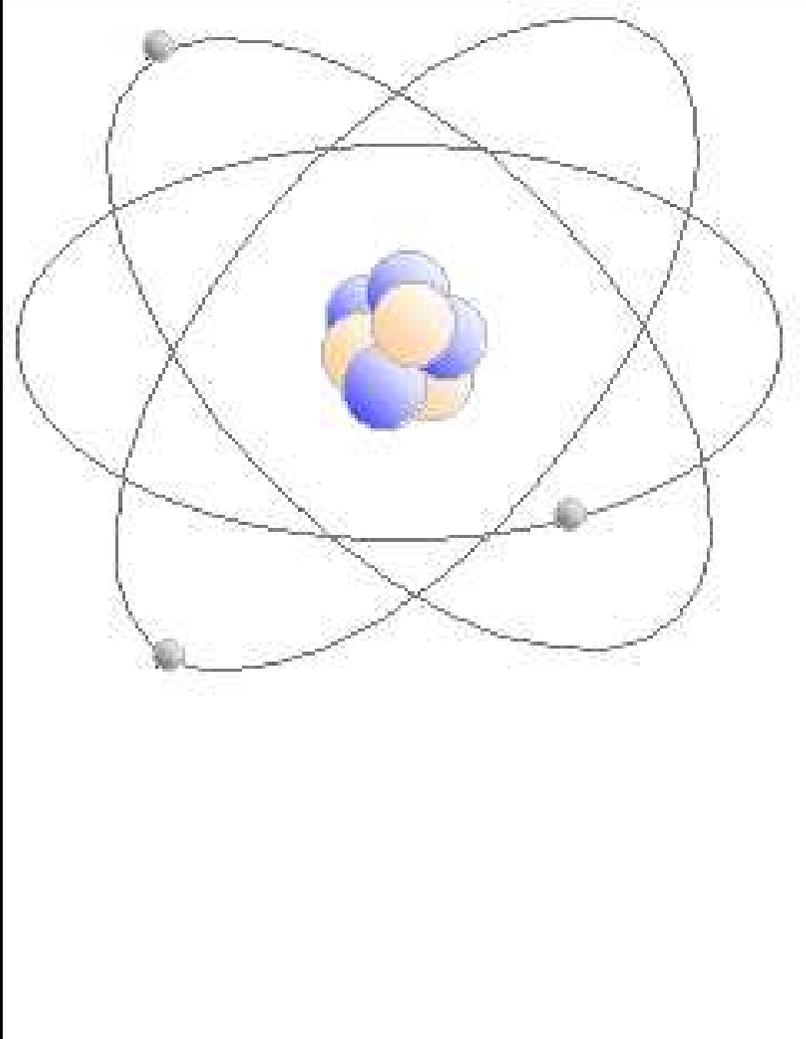
LOUIS DE BROGLIE

La lumière est composée de petits grains, les photons.

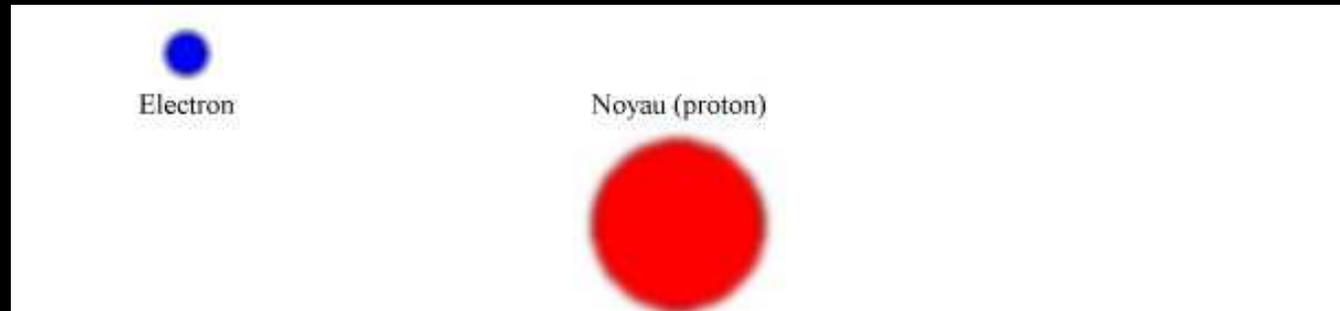
La lumière est à la fois ondes et corpuscules



L'ATOME



L'atome d'Hydrogène est un atome simple



L'électron n'est pas localisé en un point

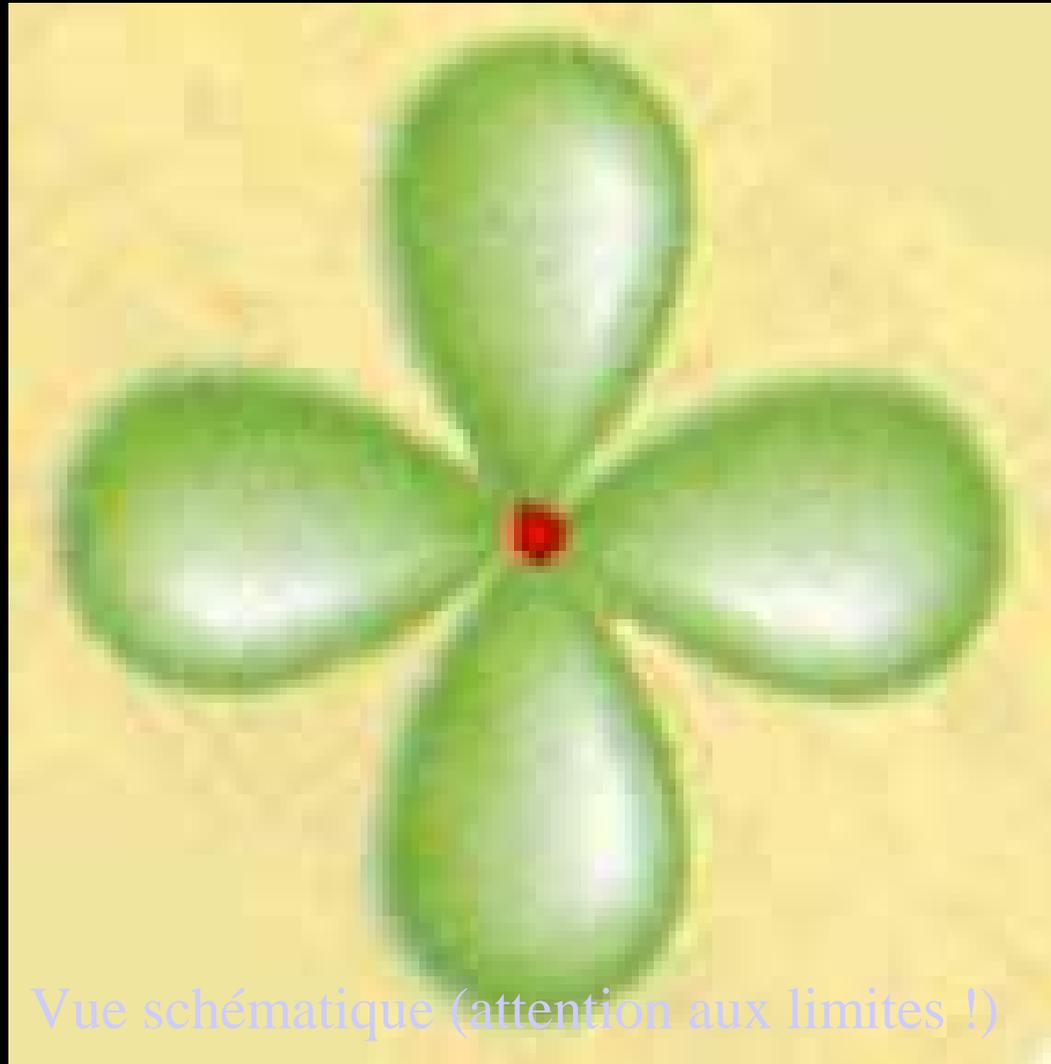
L'électron n'a pas de trajectoire mais est présent dans un volume appelé orbitale

On ne perçoit qu'une probabilité de présence pour un point donné de l'espace

L'électron bouge mais possède un état stationnaire

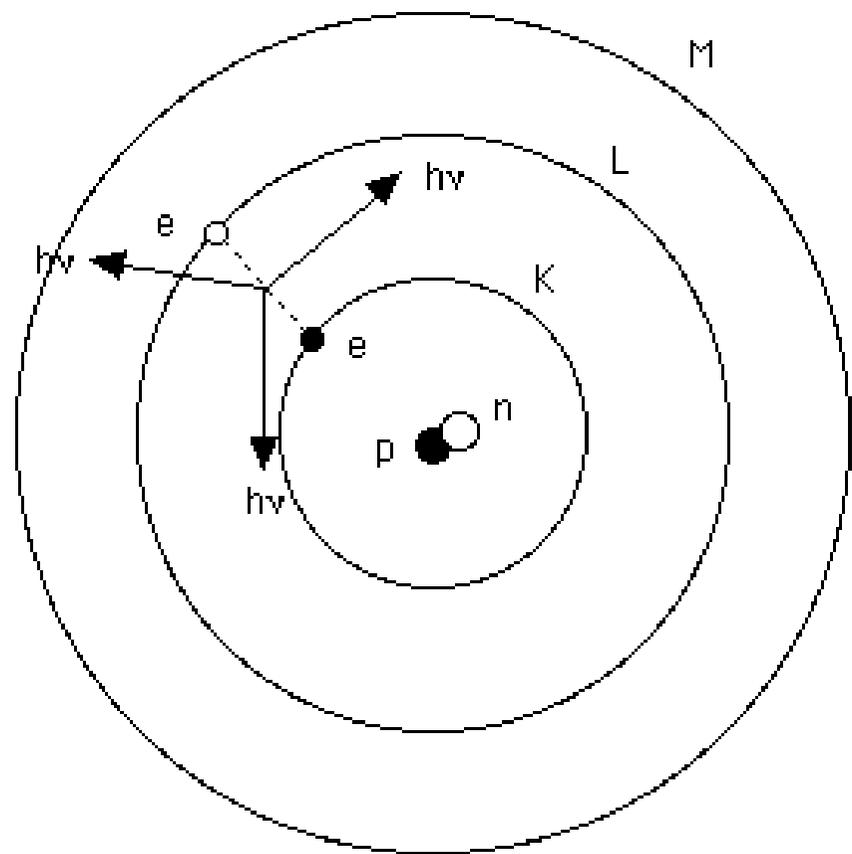
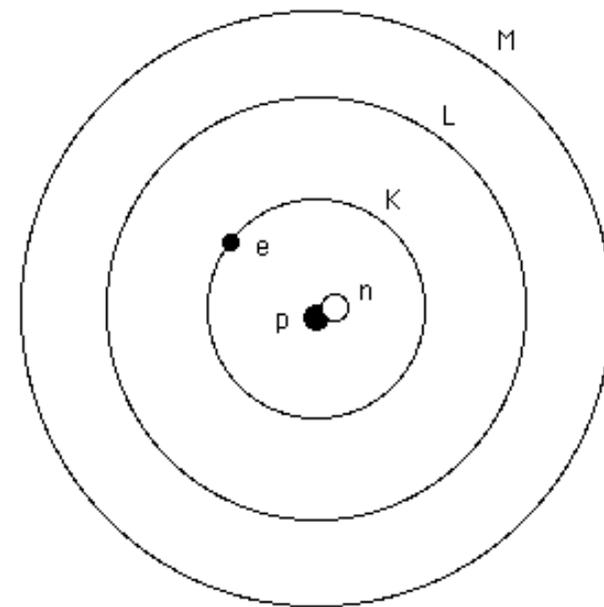
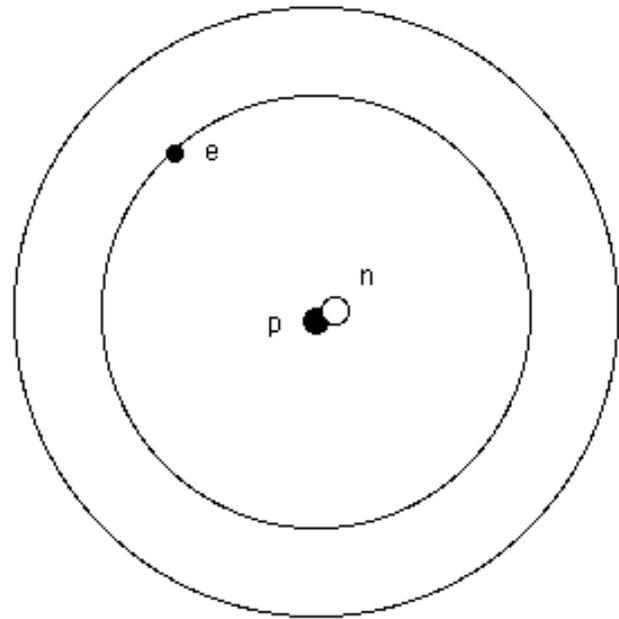
Pour les systèmes à plusieurs électrons, il n'existe pas de solution exacte mathématique

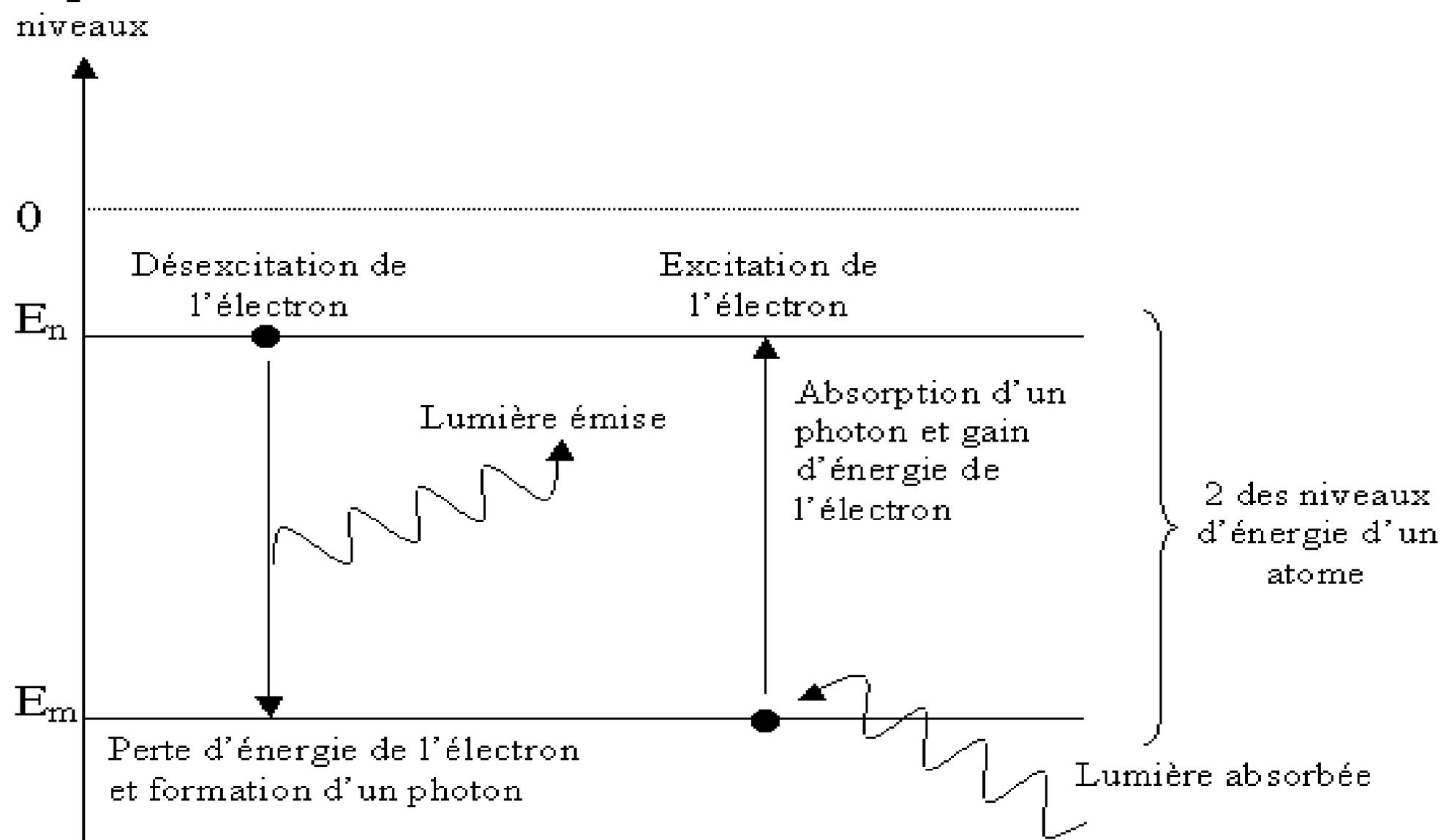
L 'atome d'hydrogène, (Orbitale)



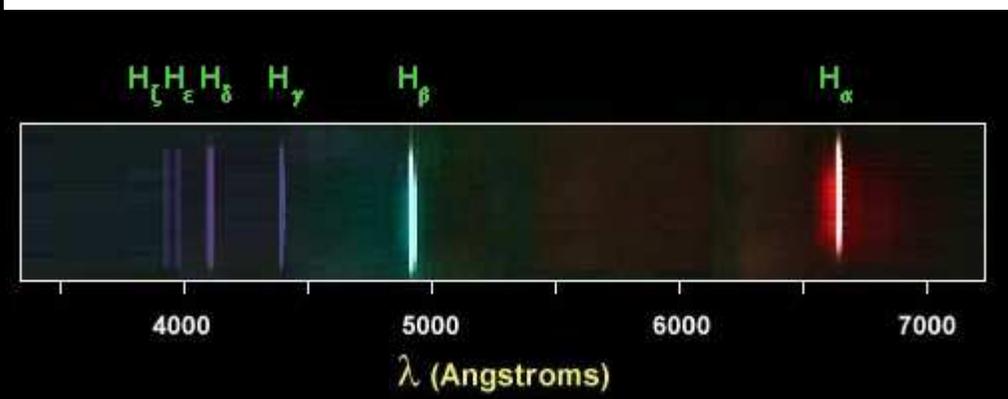
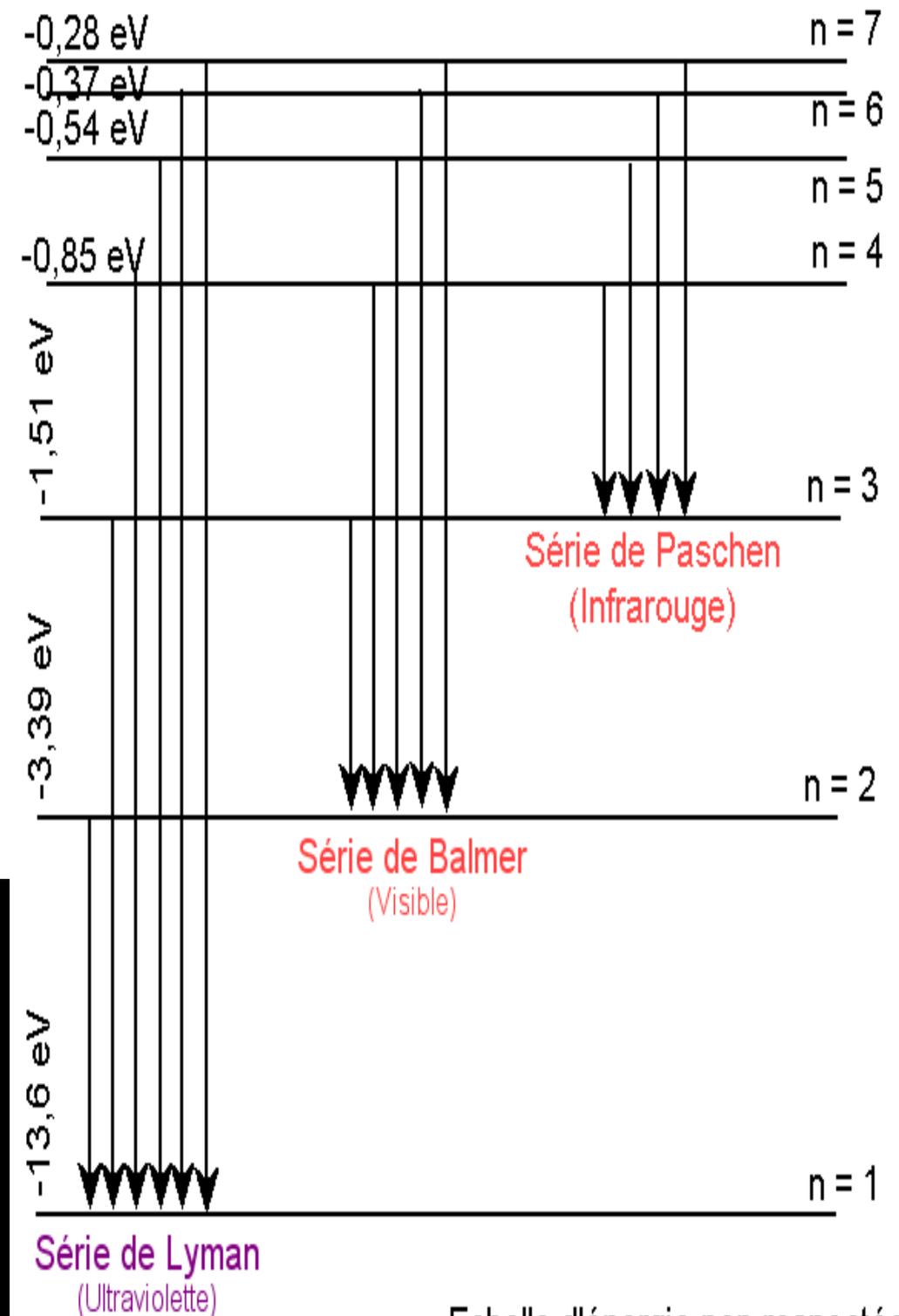
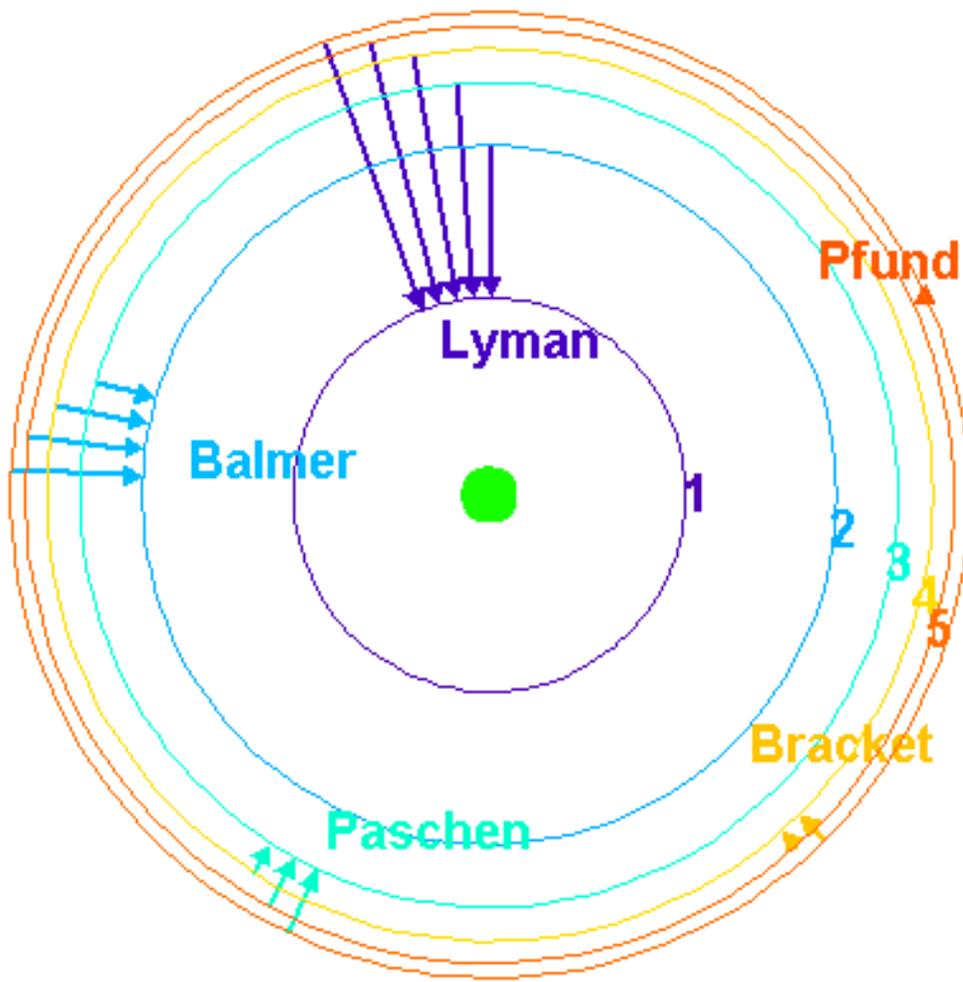
20 Angströms





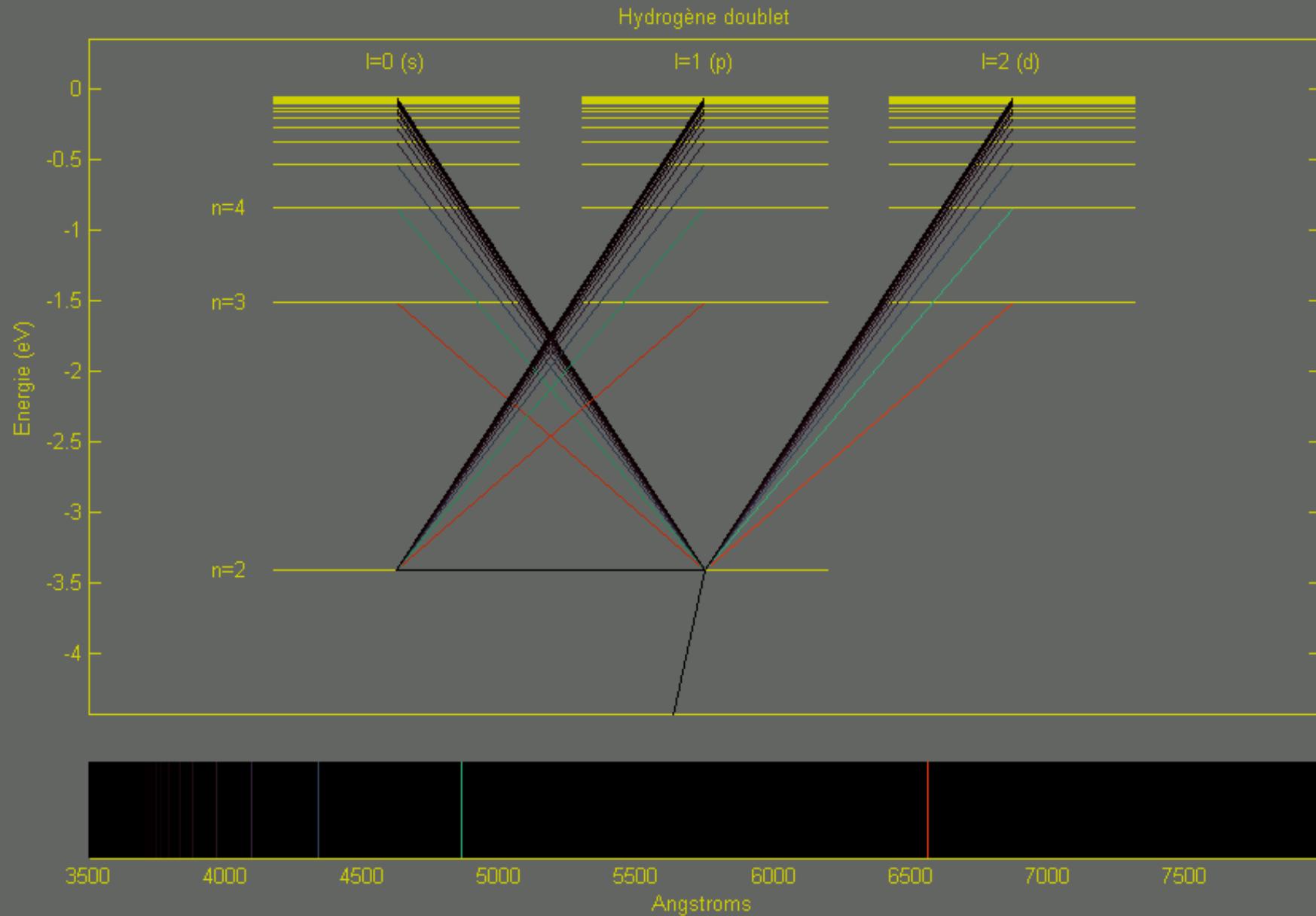


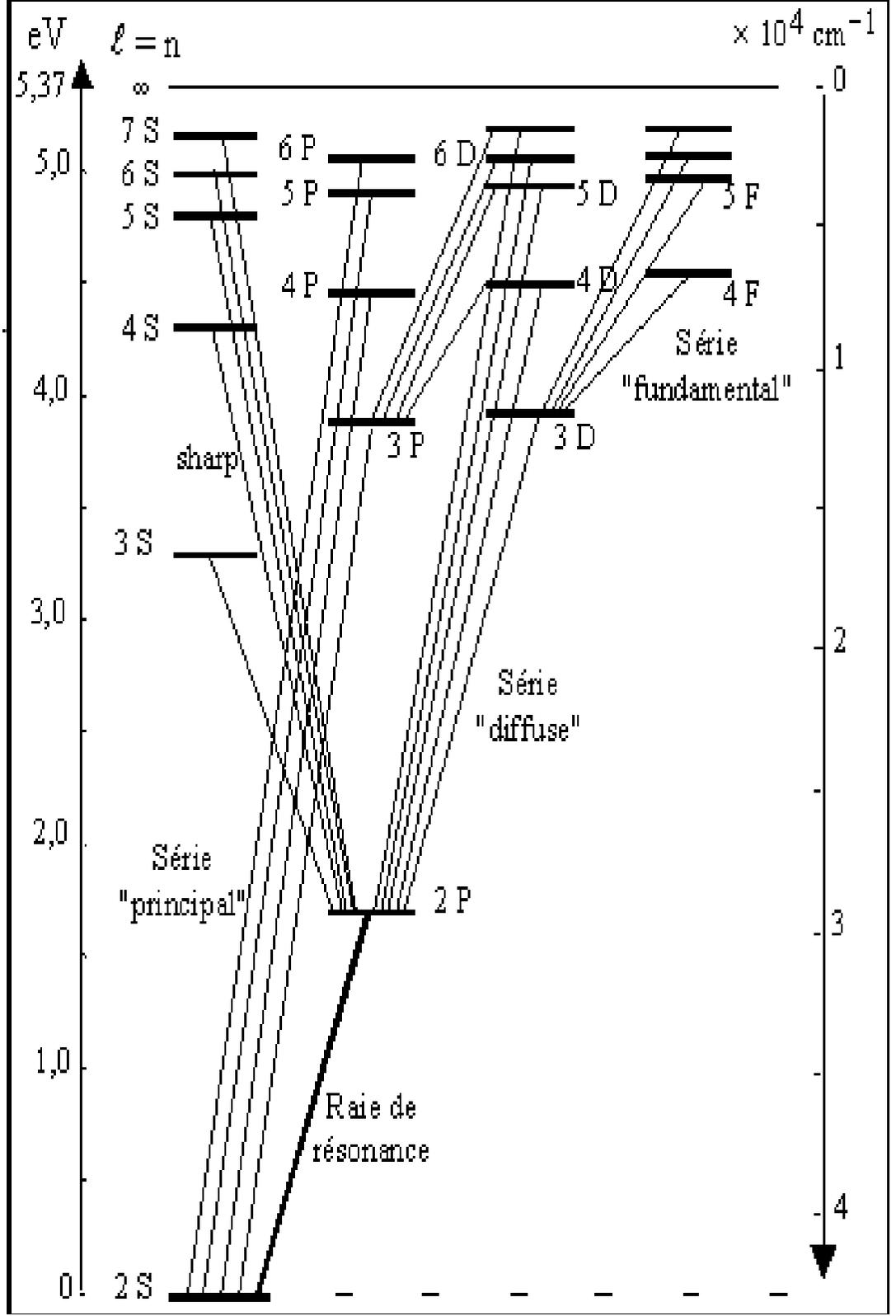
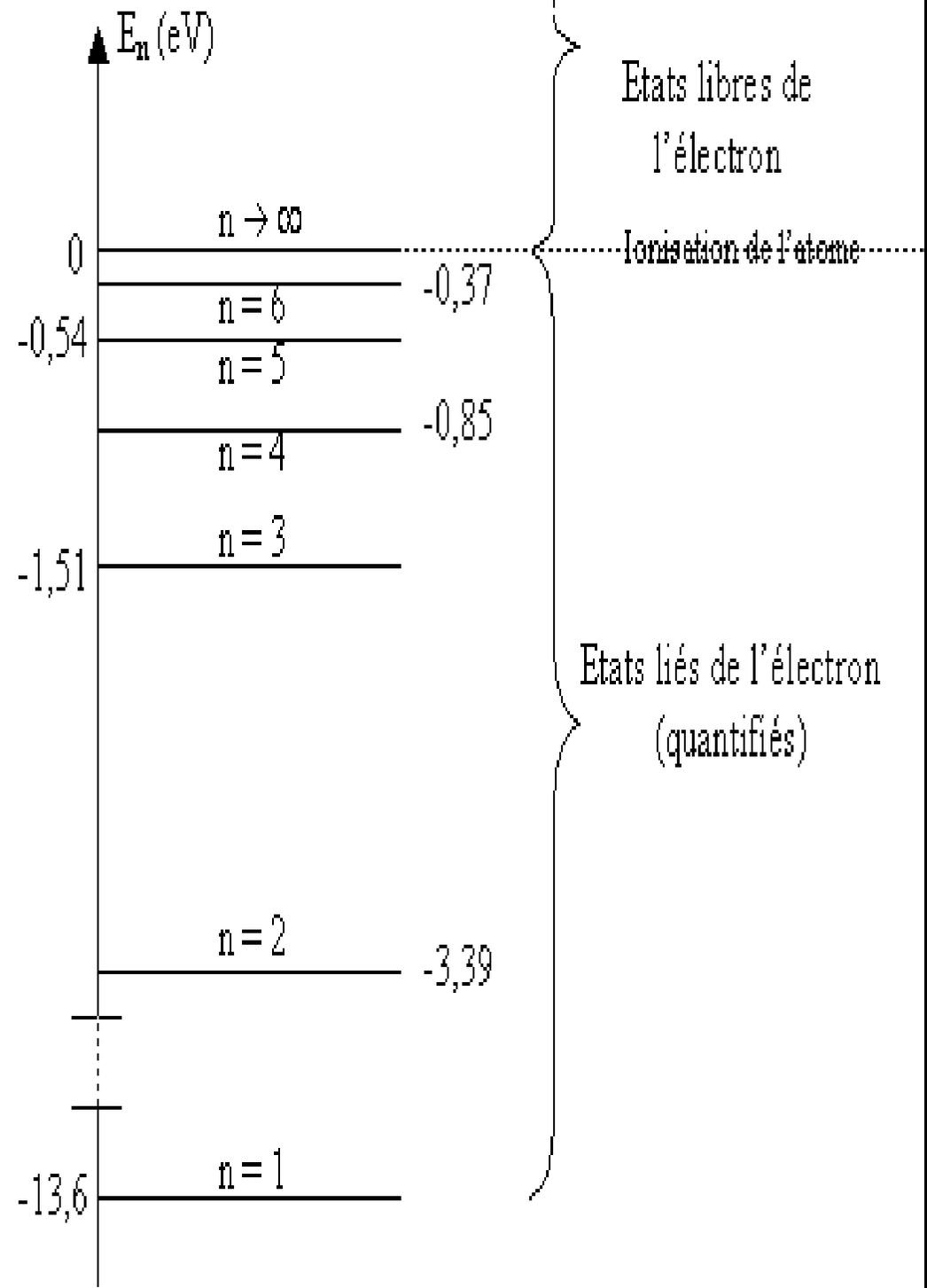
$$\Delta E = |E_n - E_m| = h\nu = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{\Delta E}$$



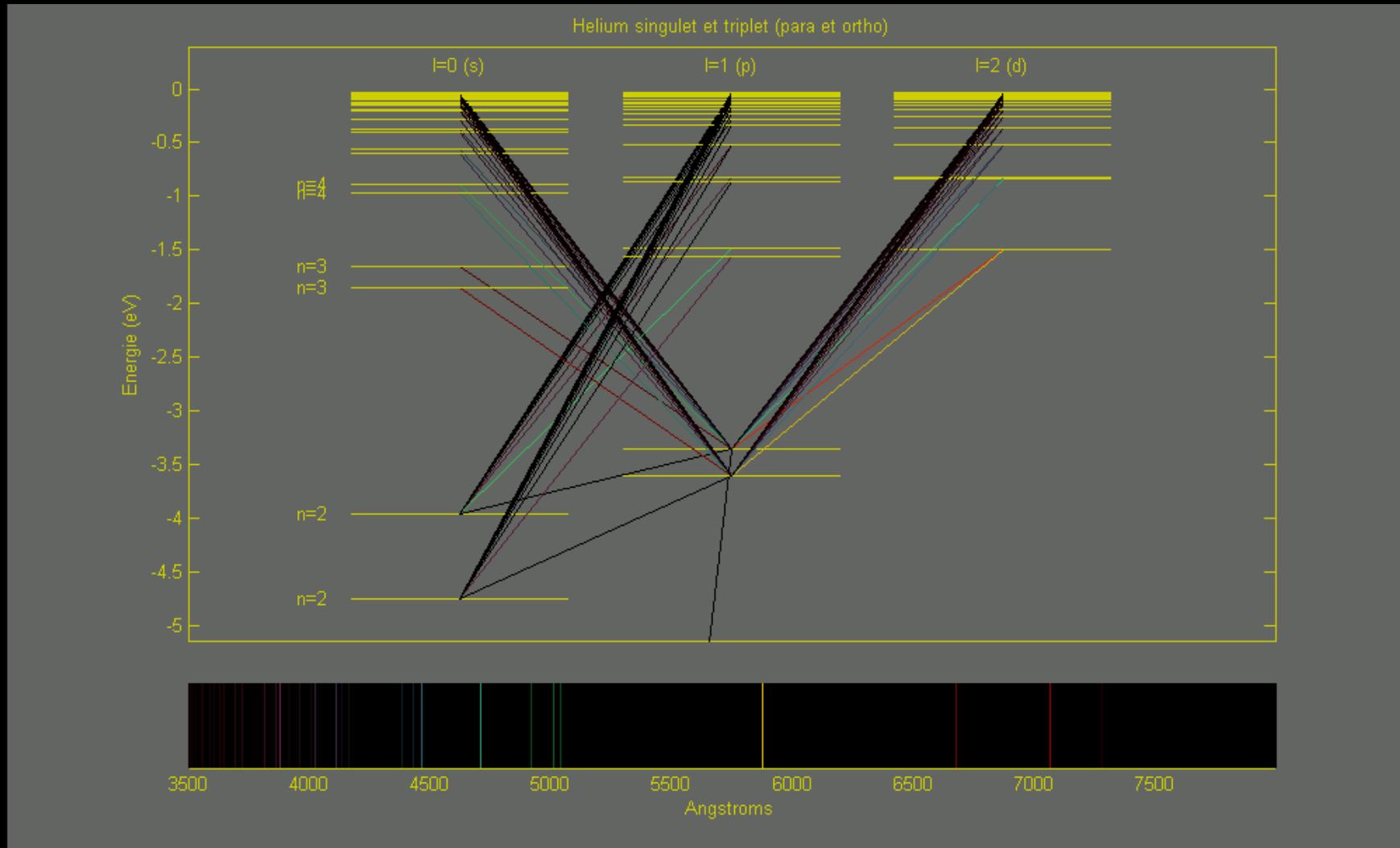
Echelle d'énergie non respectée

Raies de l'hydrogène série de Balmer

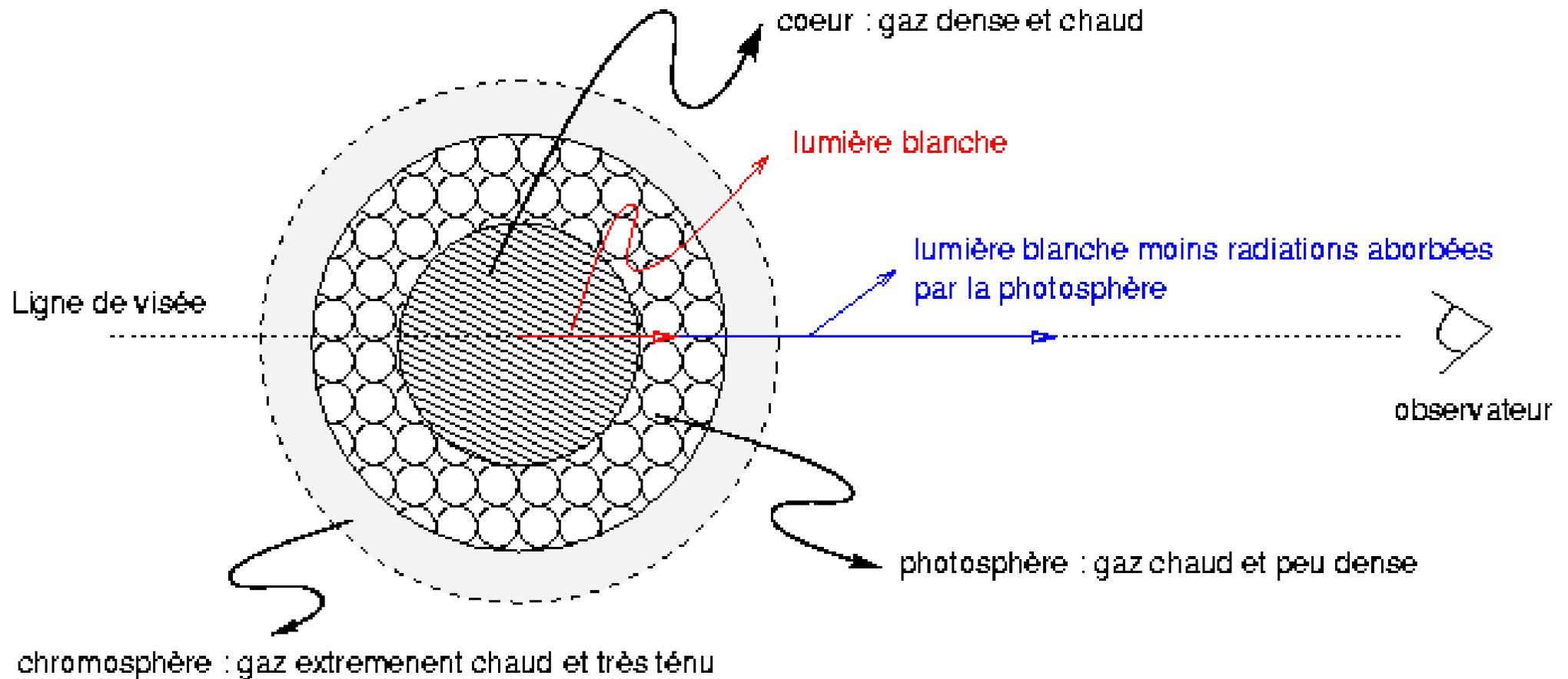


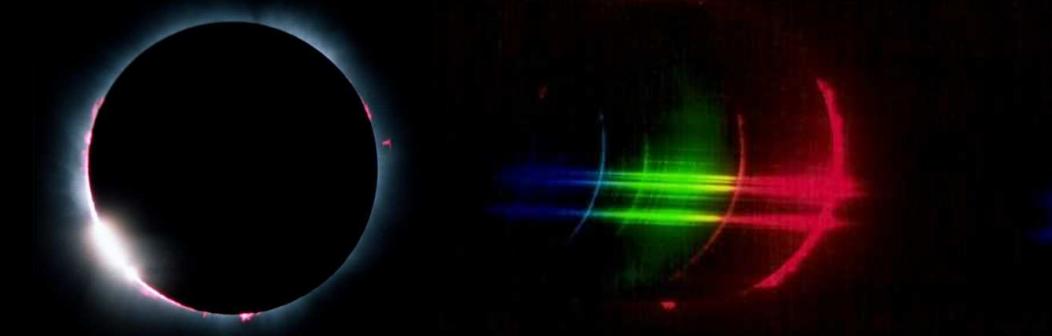
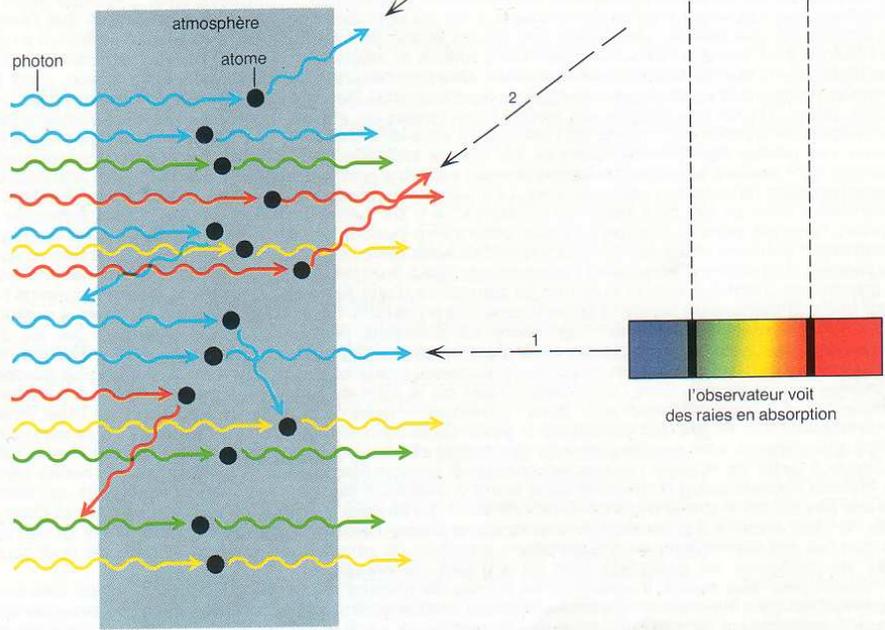
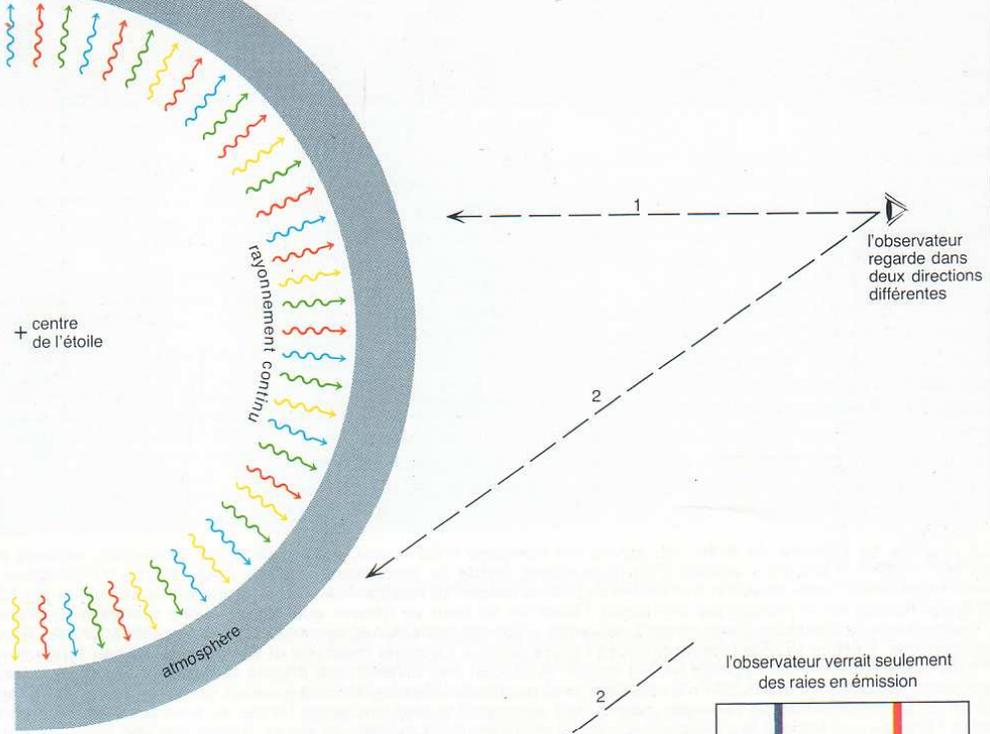


Raies de l'Hélium, série de Balmer

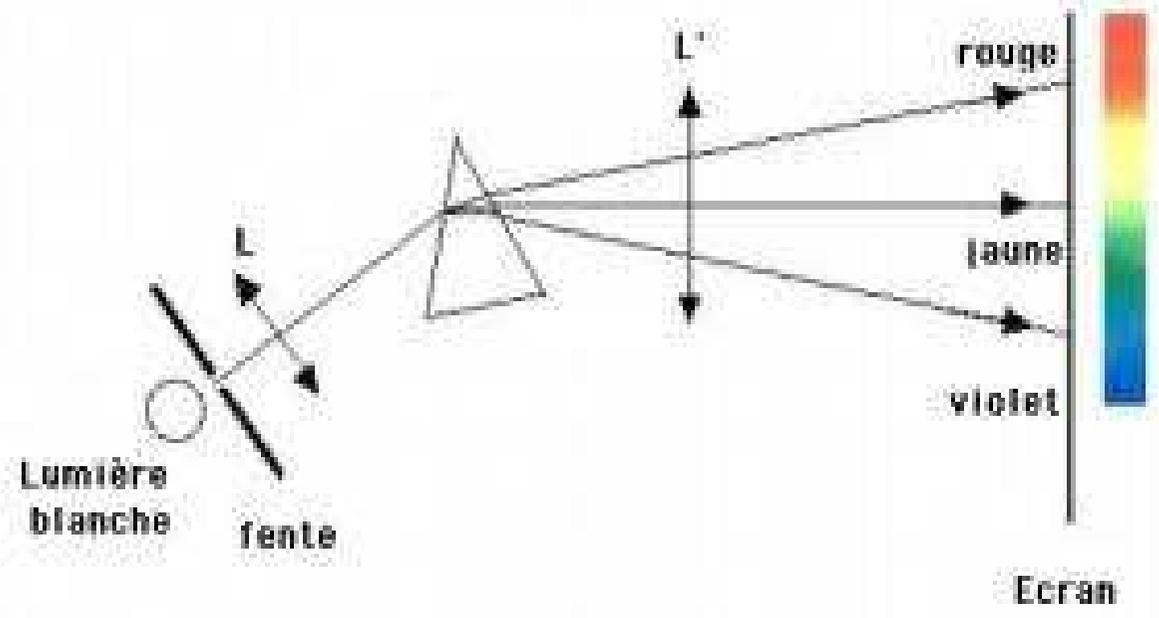


Lois de Kirchoff appliquées aux étoiles

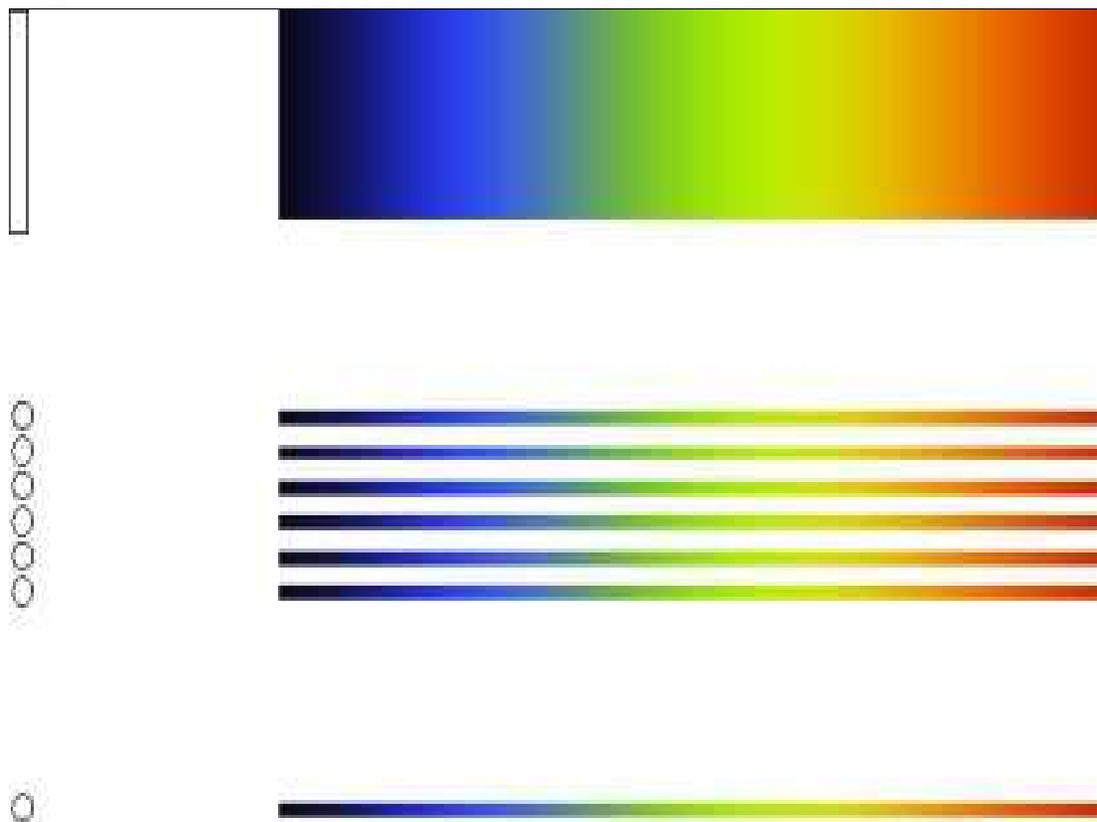
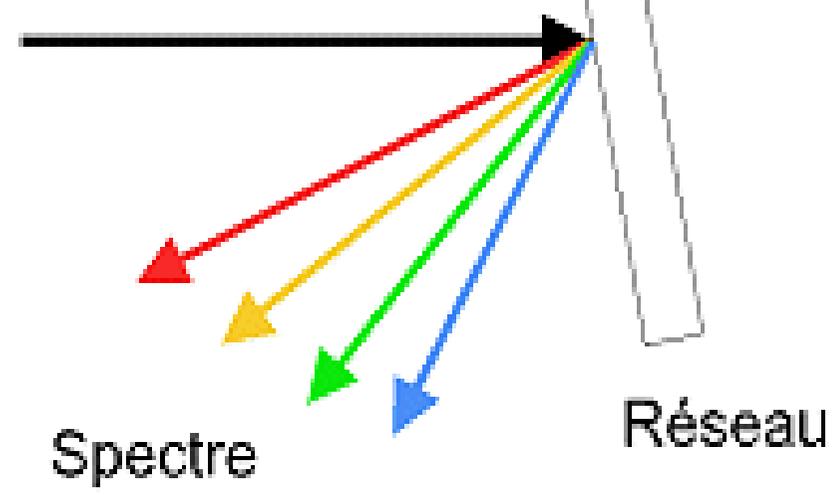


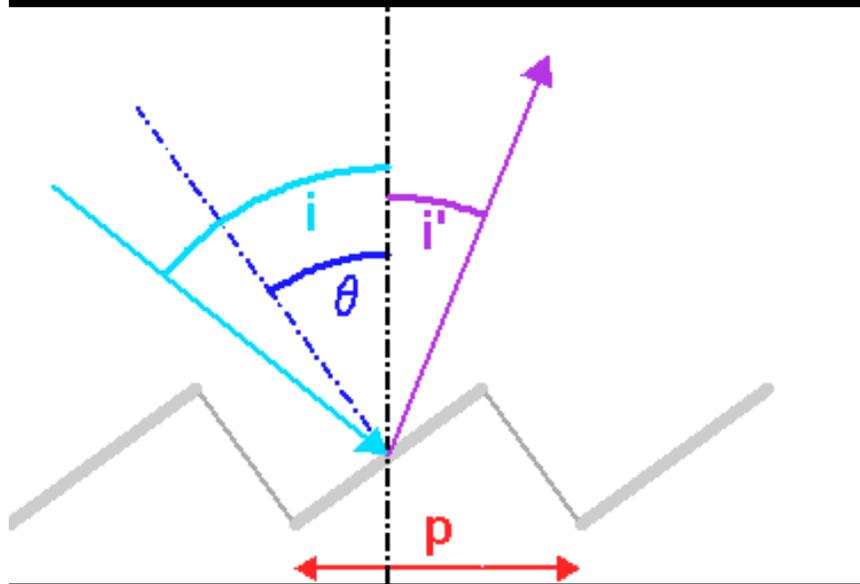




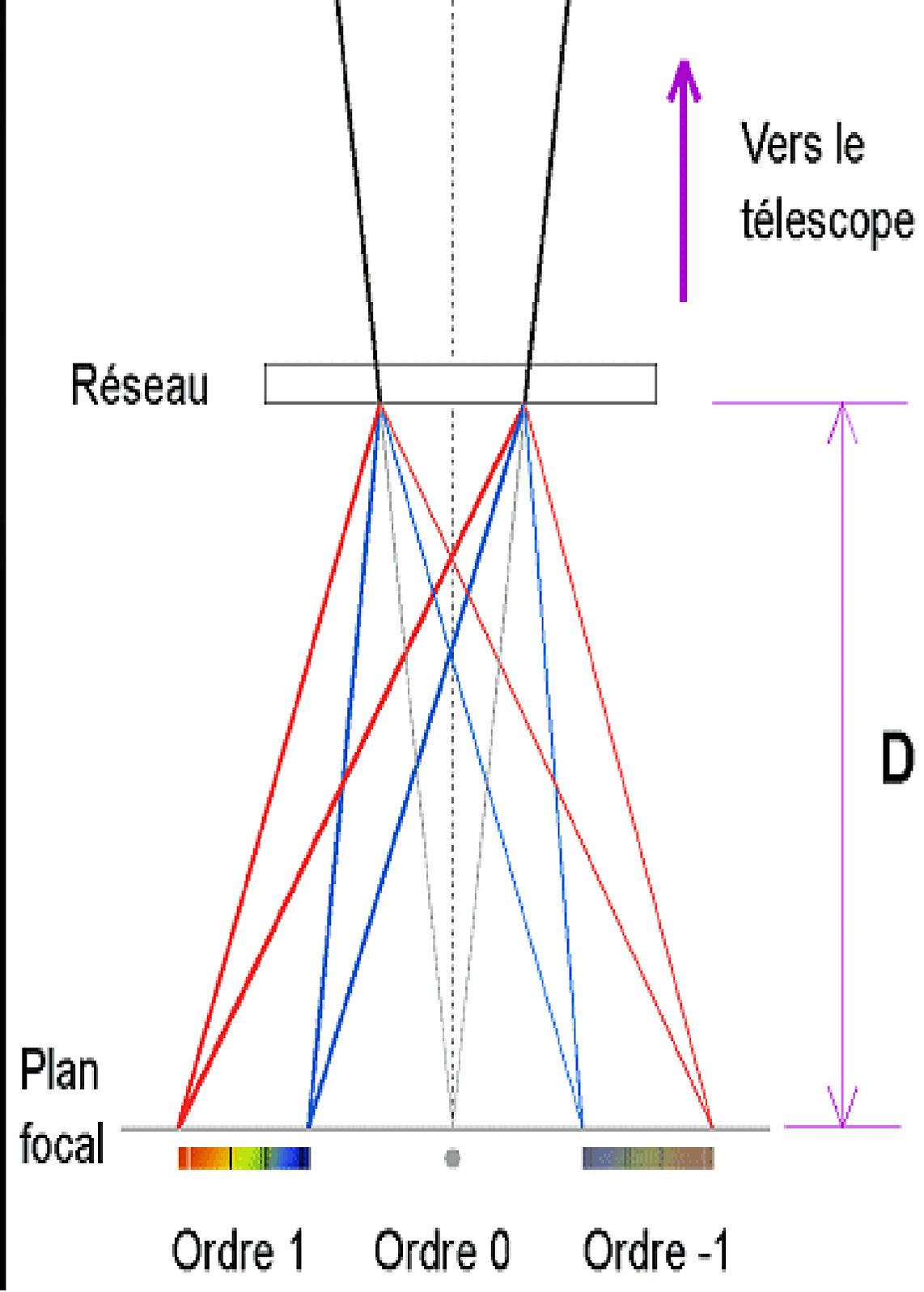
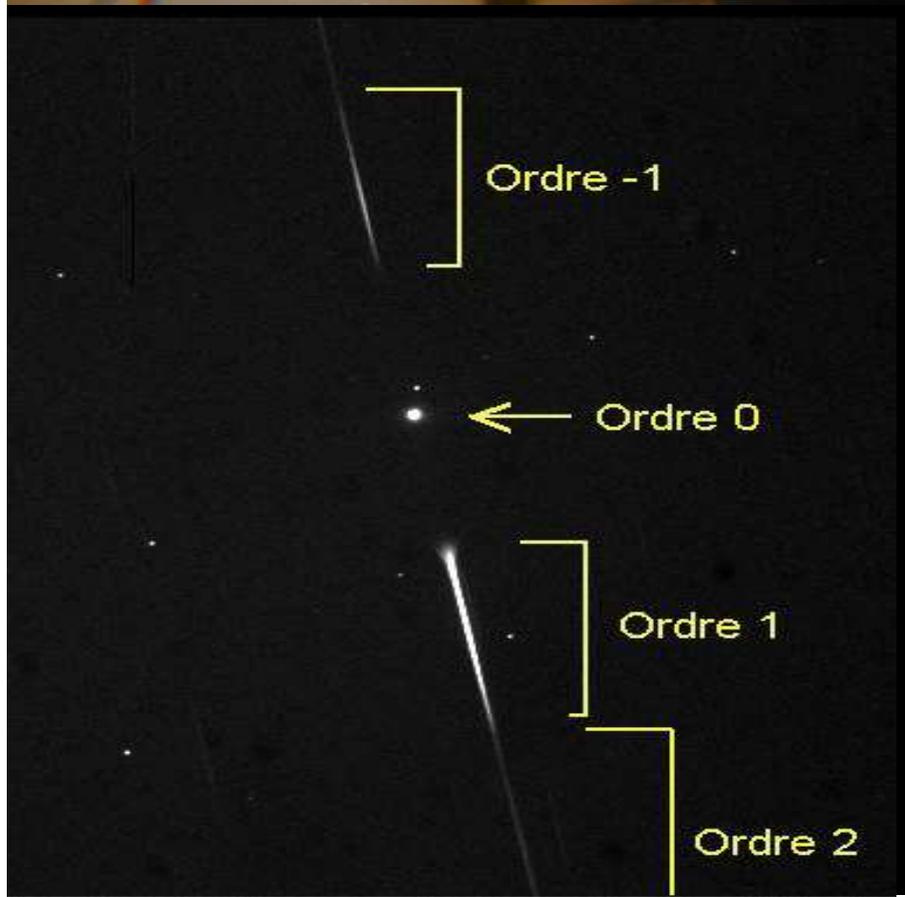
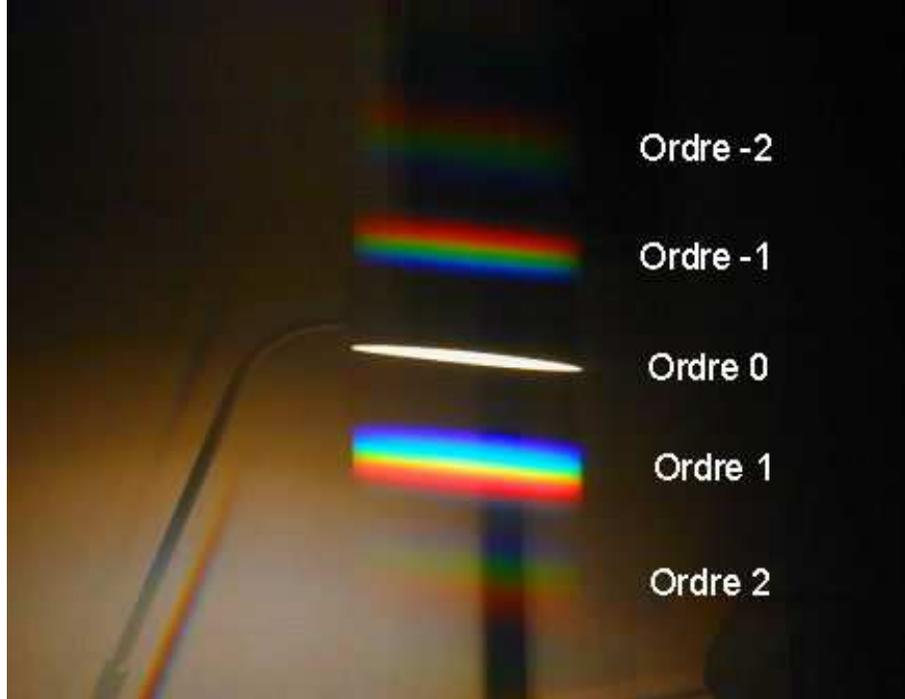


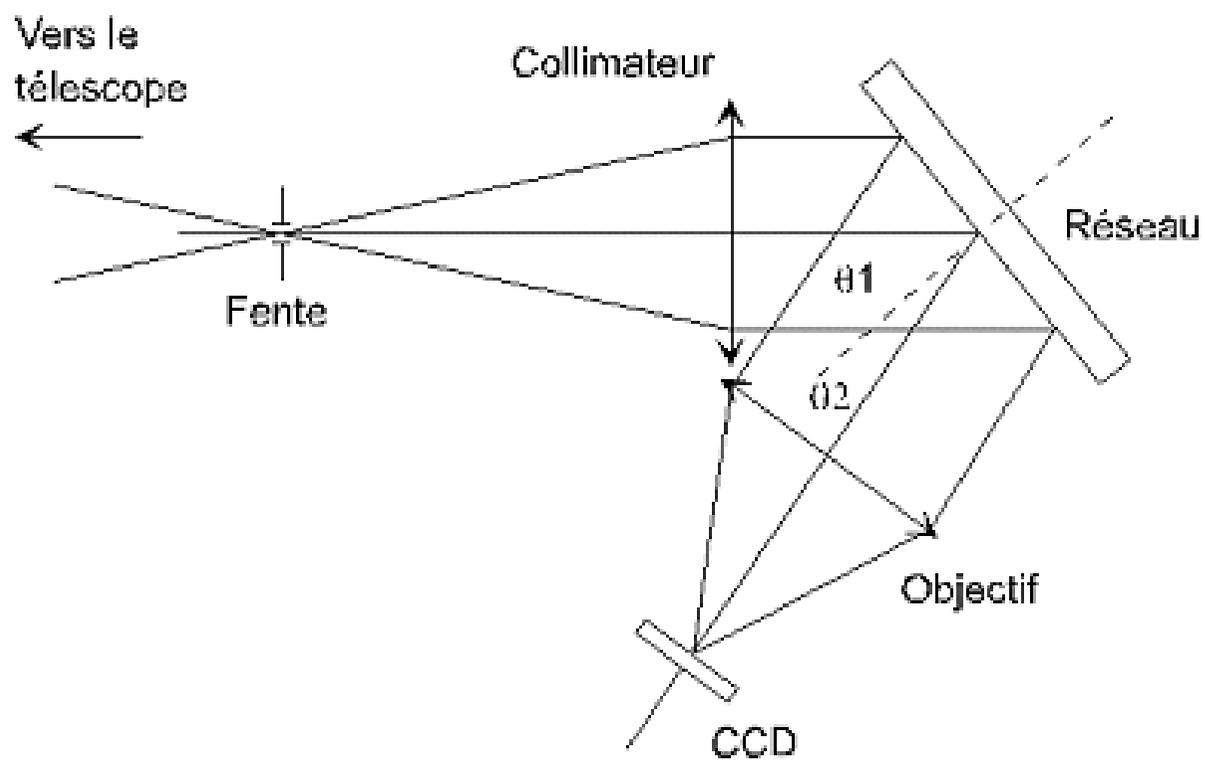
Lumière incidente



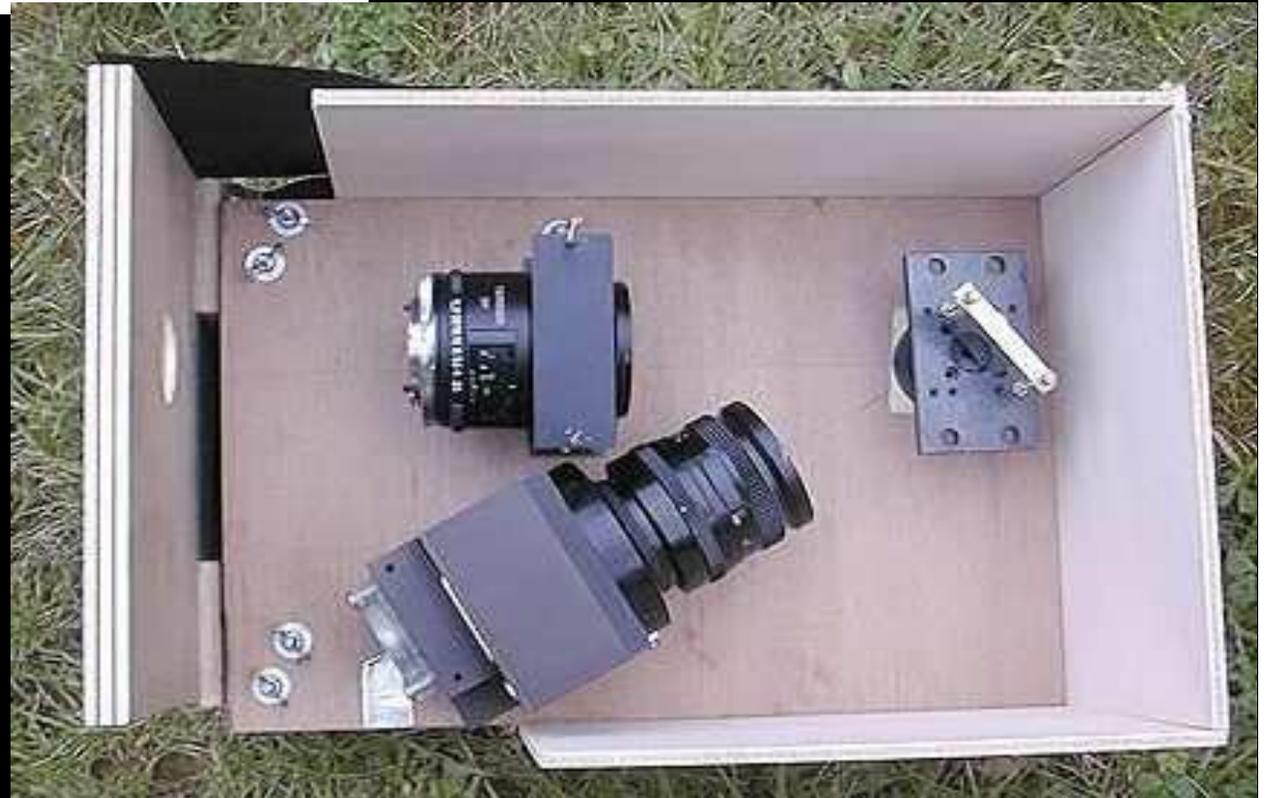


Diffraction par un réseau d'une lumière monochromatique ici un laser





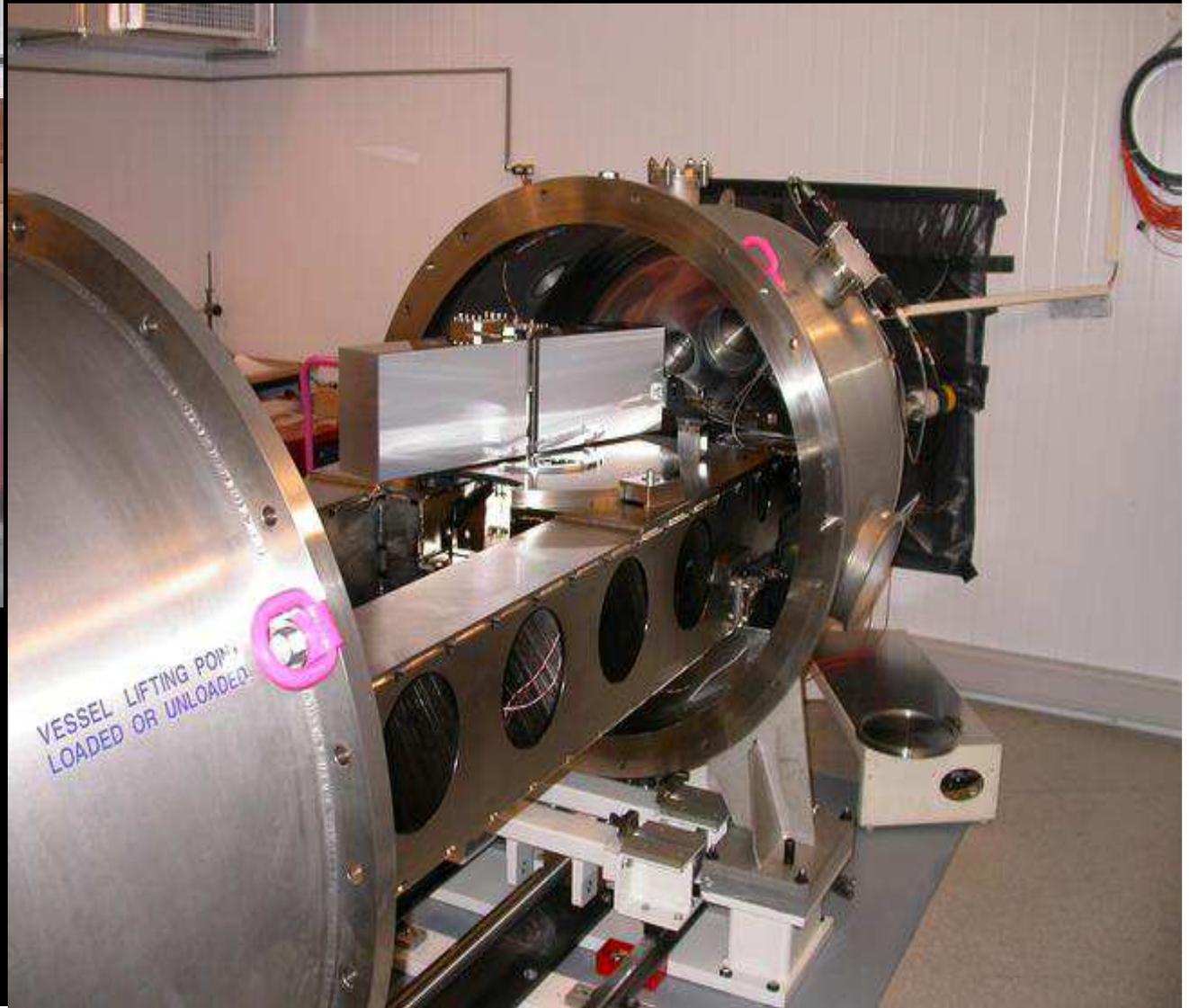
Spectroscopie amateur

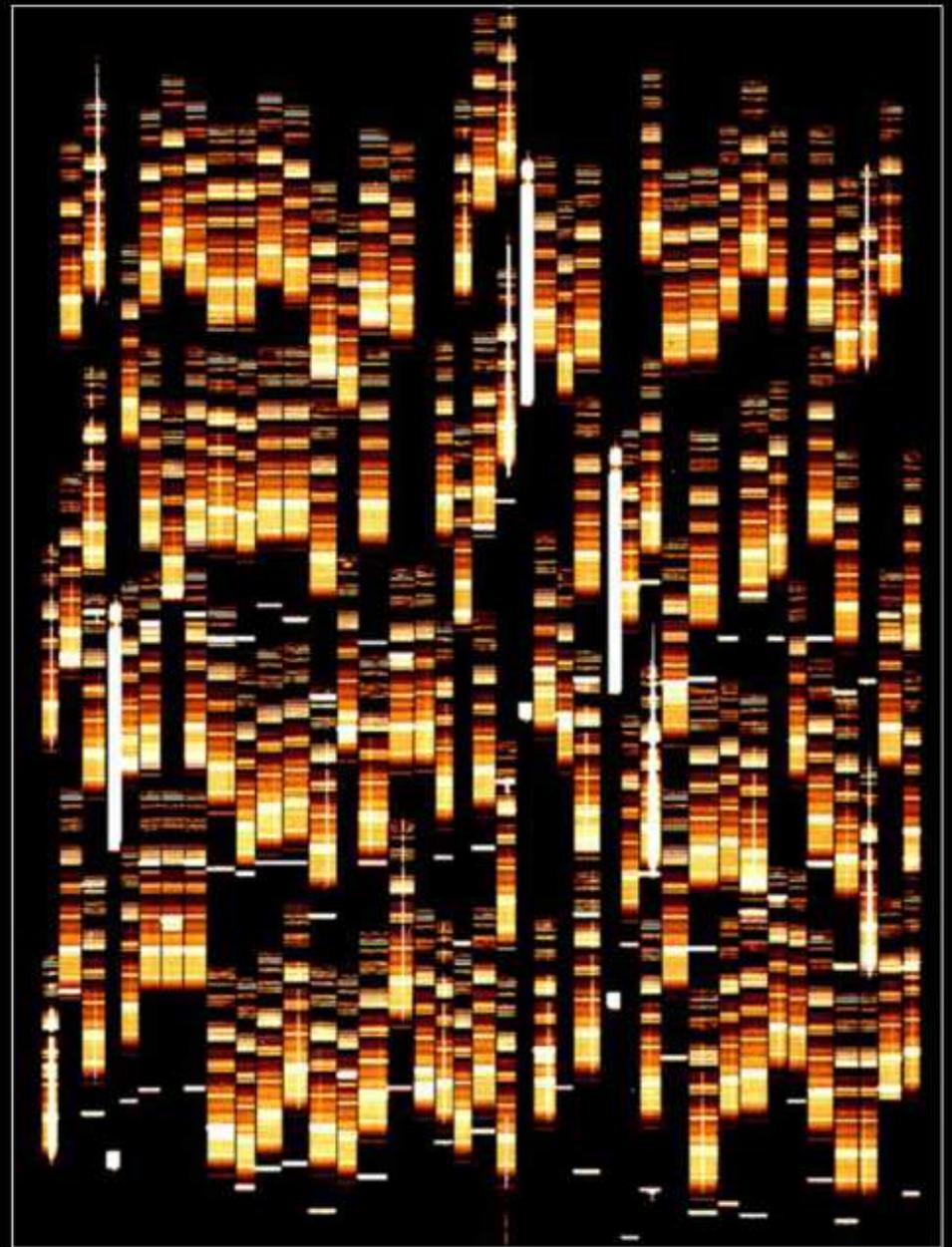
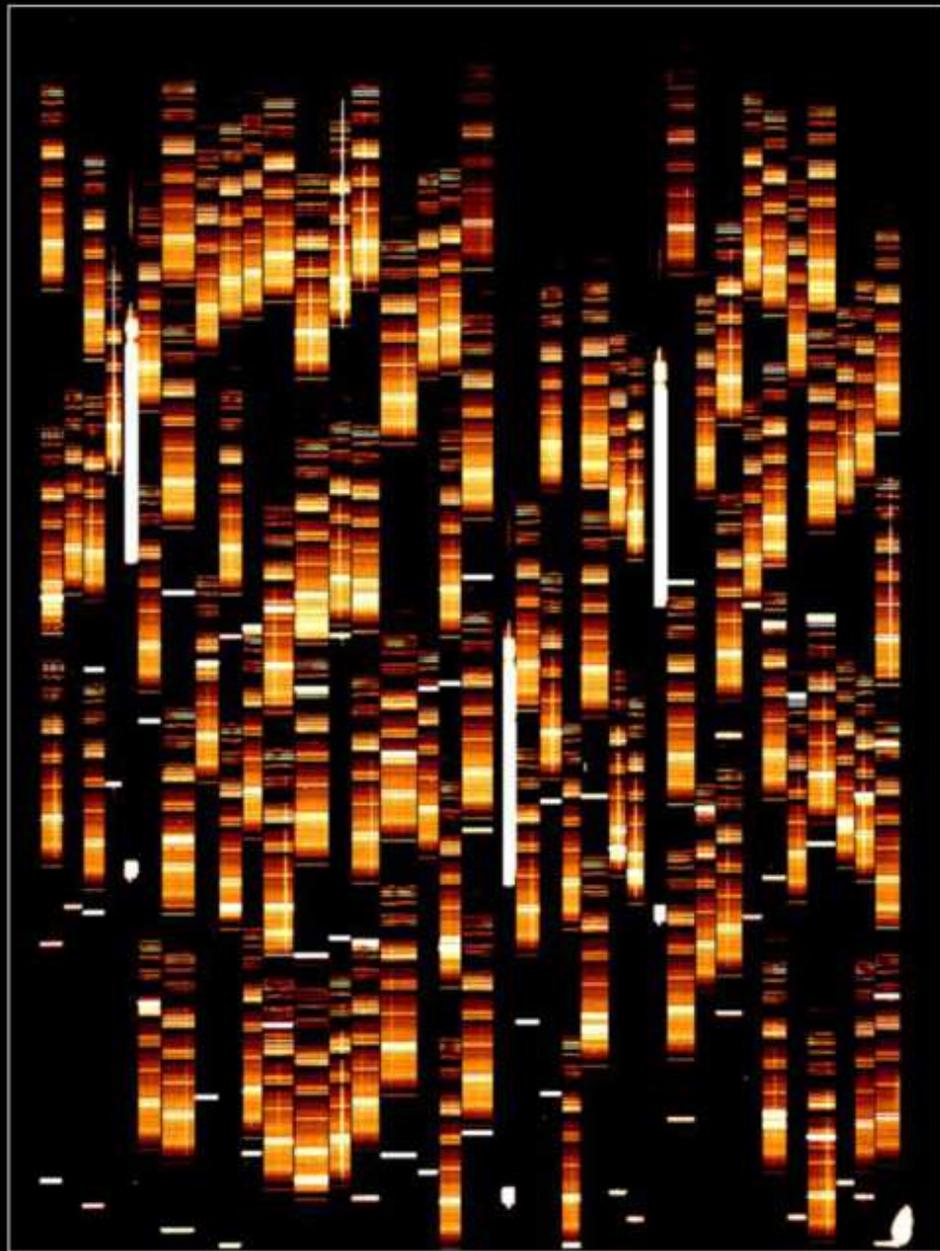




Spectroscopy FORS 1
VLT

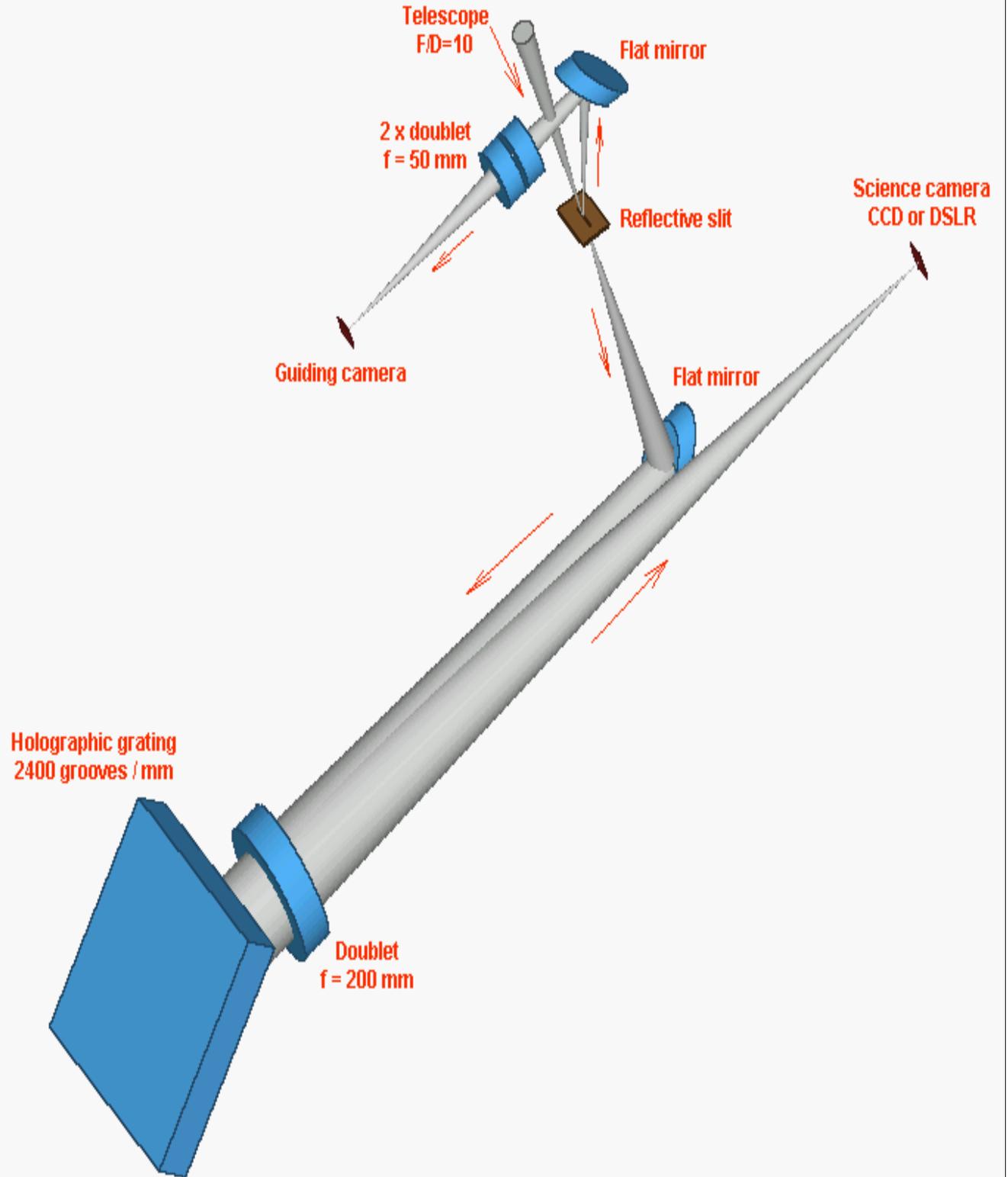
Spectroscopy Harp VLT





First VIMOS Spectra of Faint Galaxies
(VLT MELIPAL + VIMOS)

Spectroscopy LHIRES III



PARAMETRES QUE L'ON PEUT MESURER DANS UN SPECTRE

- **Mesure de la température:** Par la détermination du profil de la fonction de Planck.
- **Identification des éléments chimiques:** Par la mise en évidence des raies propres à chaque corps.
- **Détermination des abondances:** Par la mesure de l'intensité des raies d'un élément par rapport aux autres.
- **Mesure de la pression dans la zone absorbante:** Par la mesure de l'élargissement des raies de l'ensemble des éléments présents.
- **Existence d'un champ électrique ou magnétique:** Par l'observation du dédoublement ou triplement des raies (effets Stark et Zeeman).
- **Mise en évidence d'une rotation de l'objet:** Par l'inclinaison des raies sur l'ensemble de son spectre (effet Doppler).
- **Rapprochement ou éloignement de l'objet:** Par le décalage vers le rouge ou le bleu de toutes les raies du spectre (effet Doppler/Fizeau).

Cette dernière propriété appliquée aux galaxies lointaines a permis de mettre en évidence l'expansion de l'univers.

Forme des raies: facteurs d'élargissement

Largeur naturelle, durée de vie de ou des états excités, Profil Lorentzien.

Élargissement, Doppler thermique, Profil Gaussien.

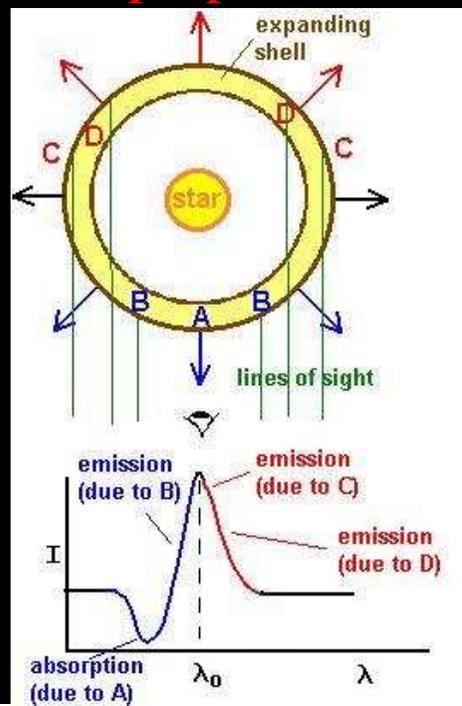
Élargissement, Doppler dynamique, rotation, expansion.

Élargissement par collision, densité du milieu, atmosphère de l'étoile plus moins dense, profil Lorentzien (Holtsmark).

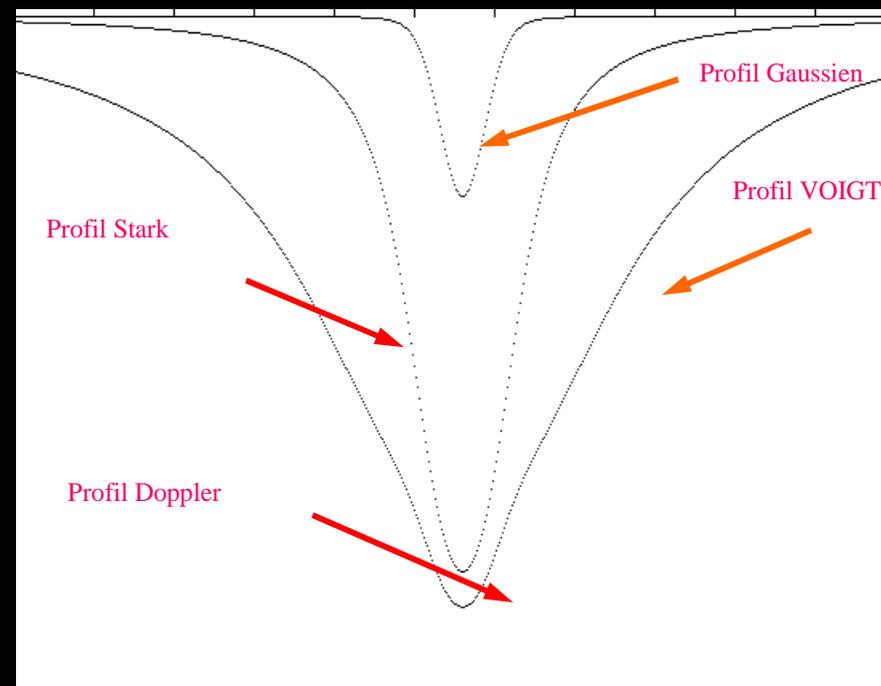
Élargissement par levée de dégénérescence, effets Zeeman et Stark.

Élargissement instrumental, résolution, dimension du réseau.

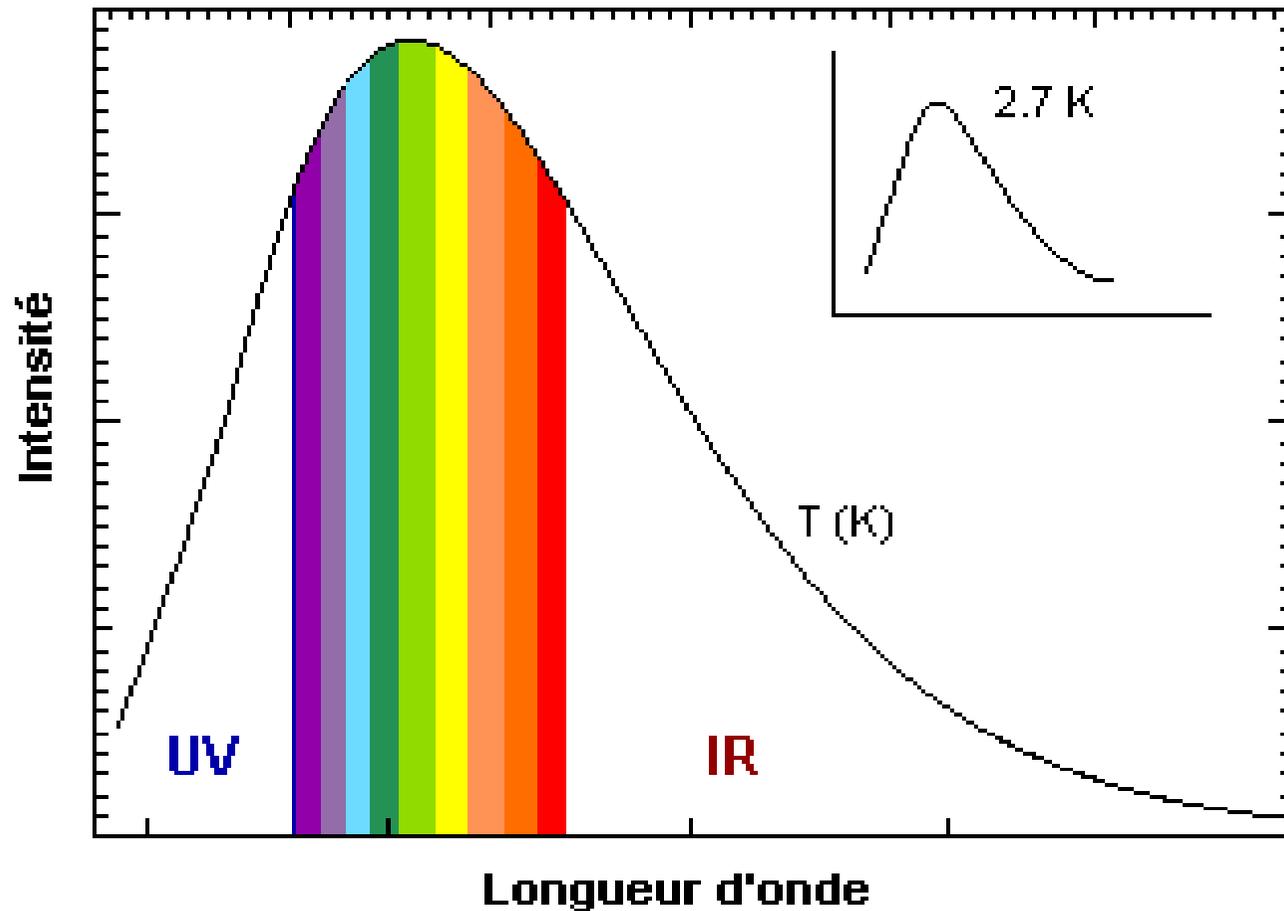
L'intensité des raies décroît lorsque l'on monte dans la série et est proportionnelle à l'efficacité d'interaction entre l'électron et le photon.



Doppler Dynamique



Fréquence

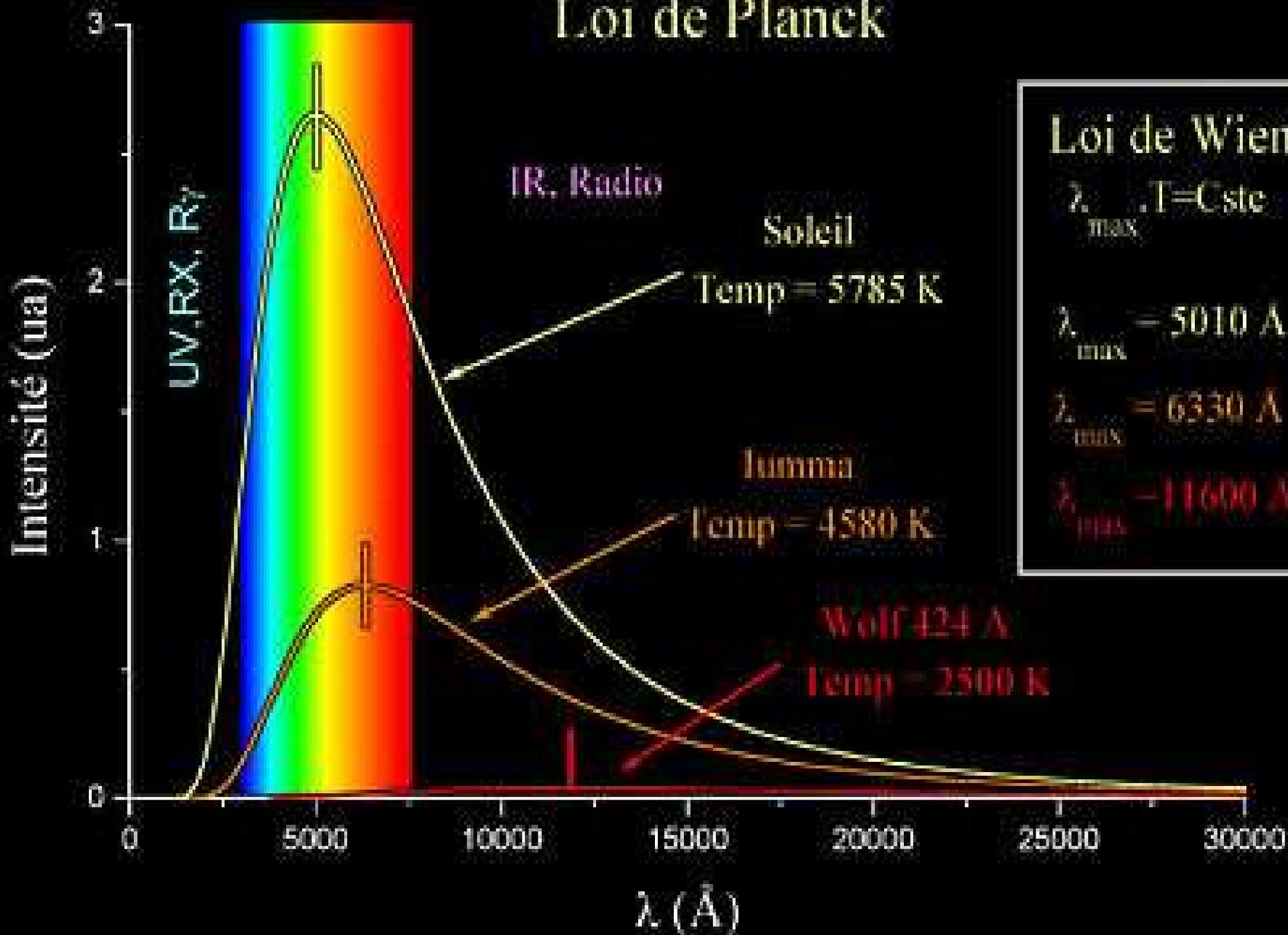


Max Planck 1858 / 1947

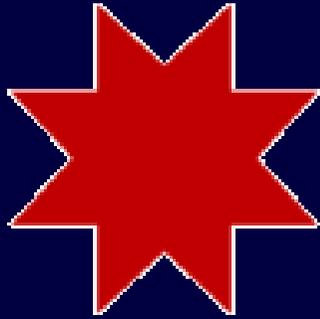
La densité de flux d'énergie pour une longueur d'onde, est donnée par **la loi de Planck**:

$$\rho_{\Gamma}(\lambda) = \frac{8\pi hc}{\lambda^5 (e^{hc/\lambda kT} - 1)}$$

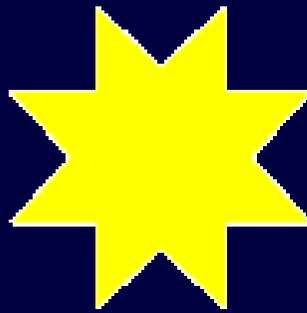
Loi de Planck



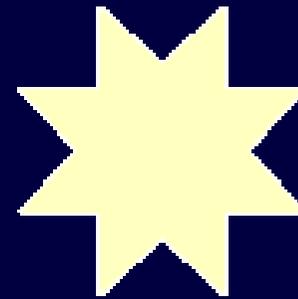
Sources lumineuses



2000 °C

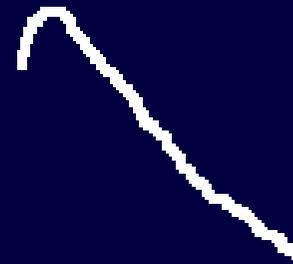


6000 °C



10000 °C

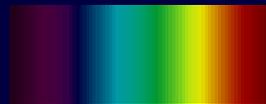
Forme du
continuum



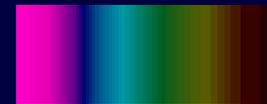
Apparence du
continuum



Le rouge domine

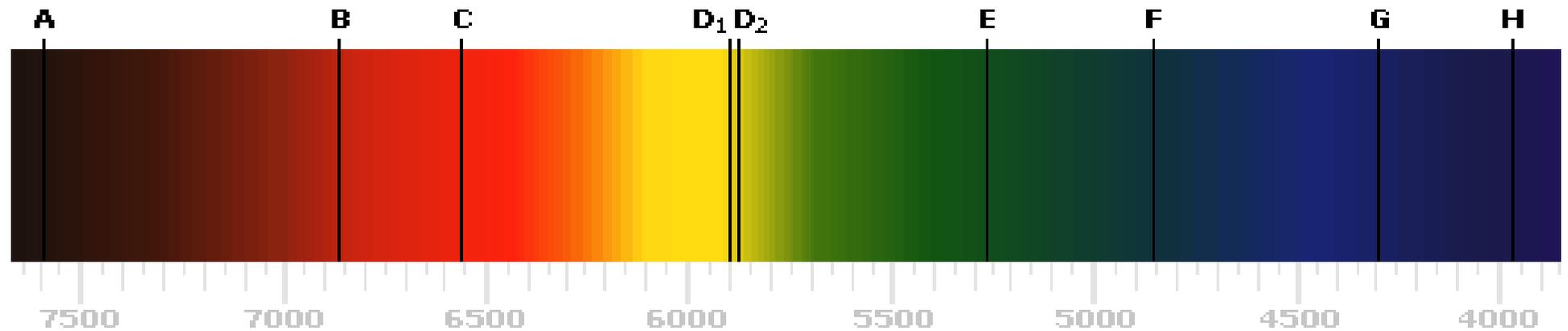


Le jaune domine



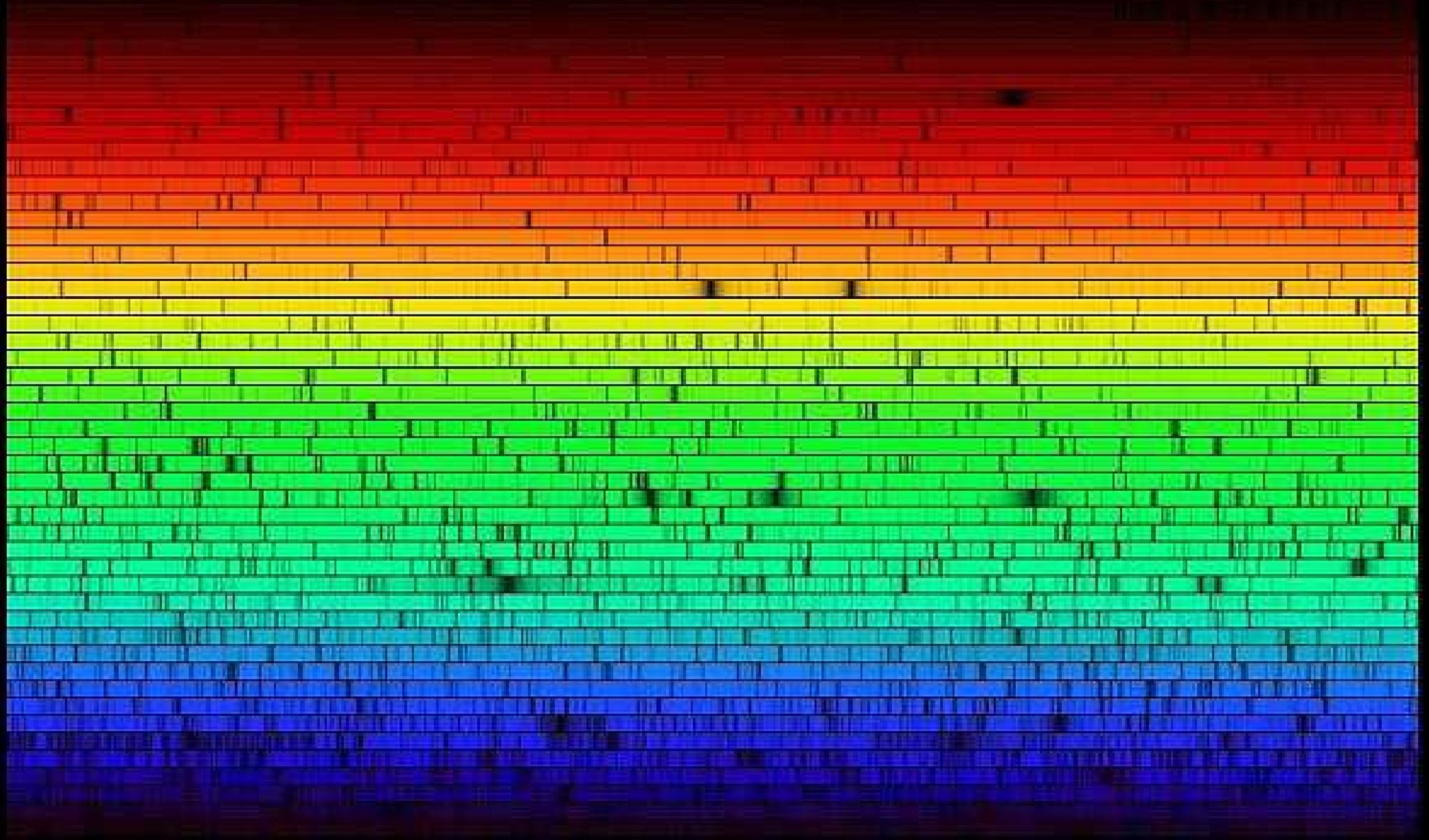
Le violet domine

Spectre du Soleil

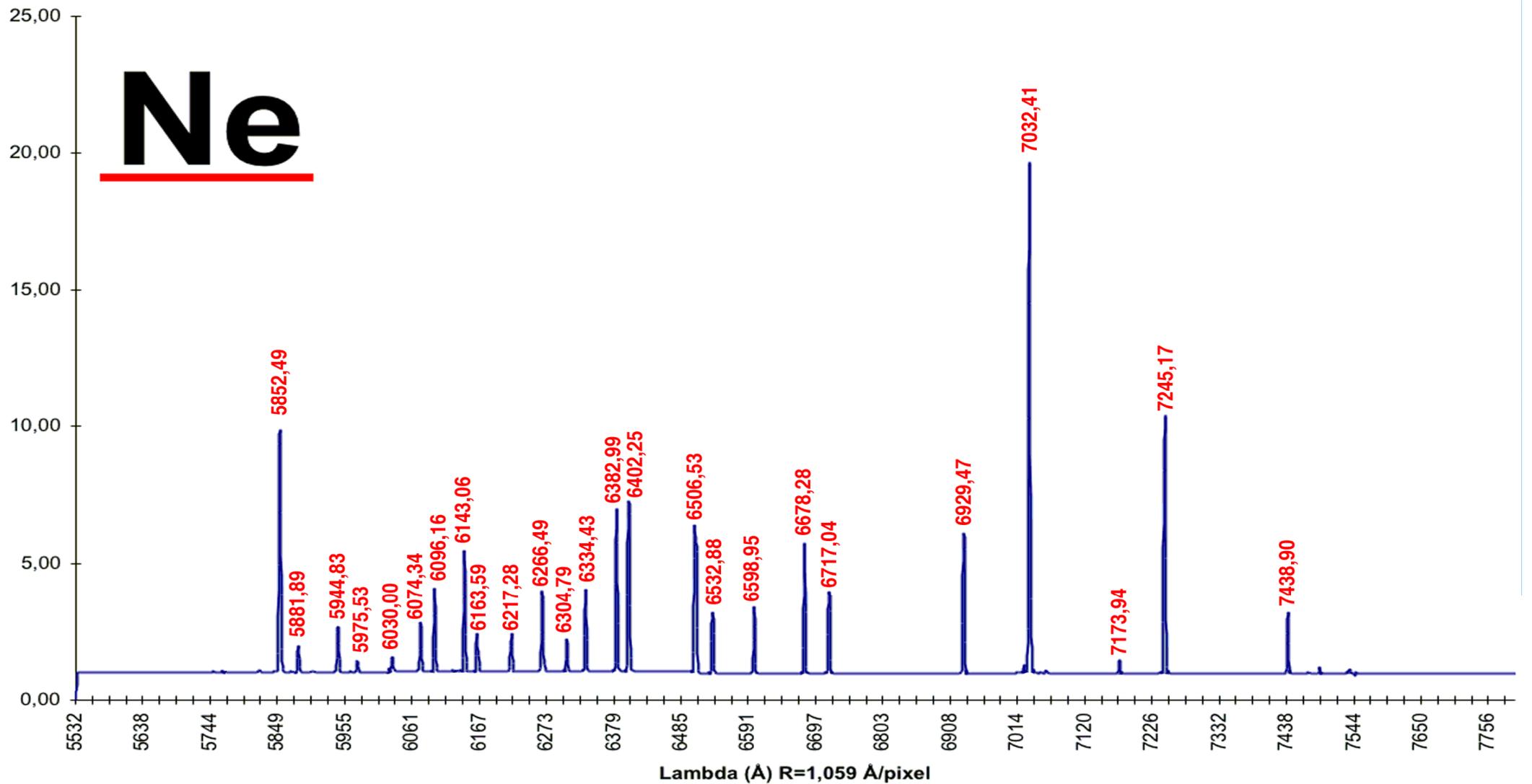
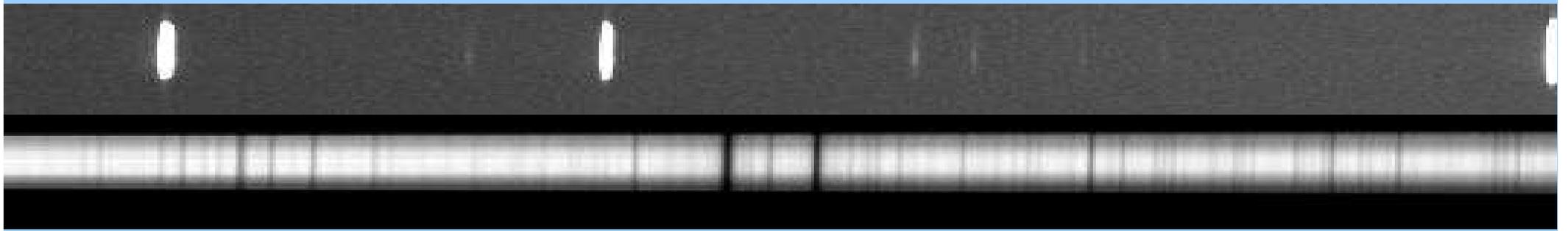


A	rouge lointain	créé par l'oxygène terrestre
B	rouge	créé par l'oxygène terrestre
C	rouge	créé par l'hydrogène solaire
D ₁	jaune	créé par le sodium solaire
D ₂	jaune	créé par le sodium solaire
E	vert	créé par le fer solaire
F	bleu	créé par l'hydrogène solaire
G	violet	créé par le calcium solaire/fer solaire
H	violet lointain	créé par le calcium solaire

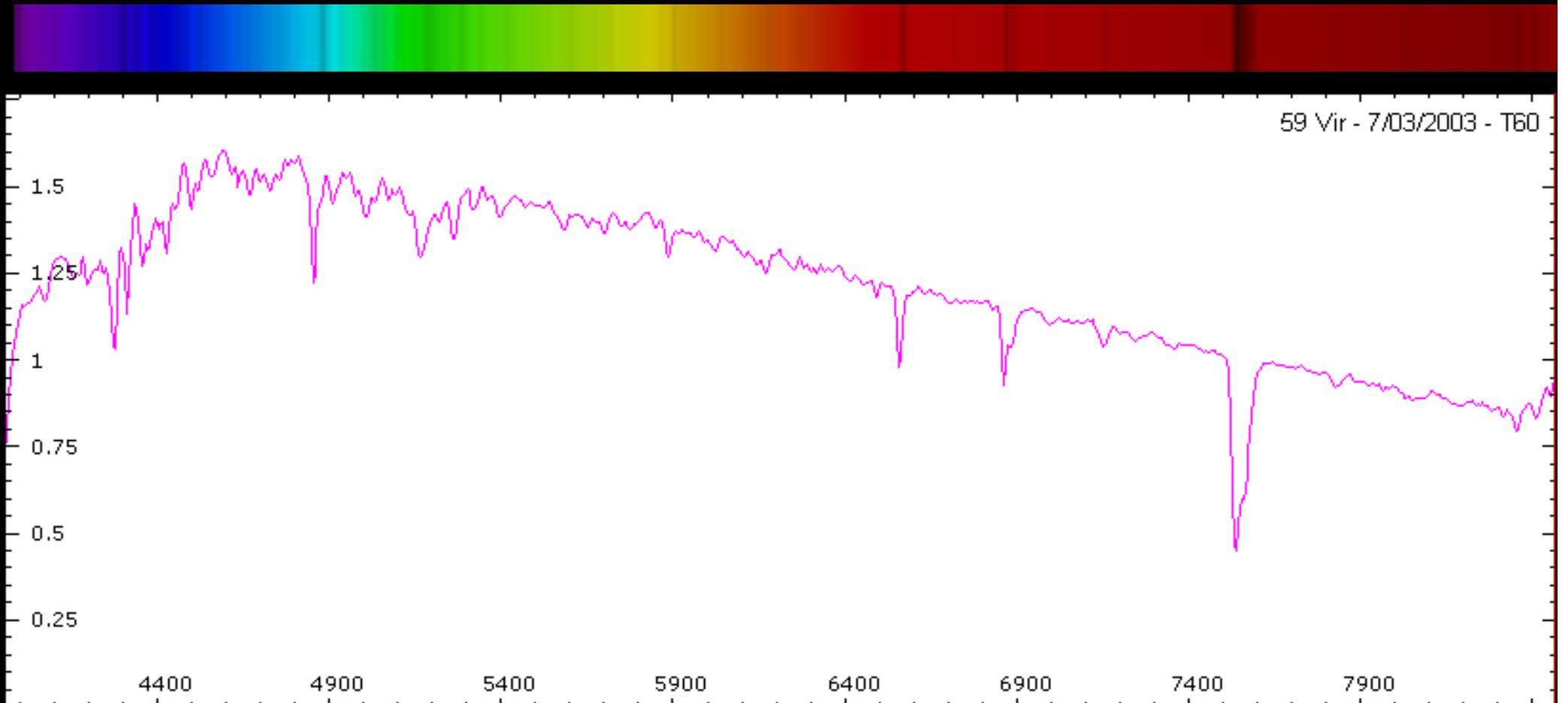
Spectre du Soleil 26000 raies dont 6000 pour le Fer



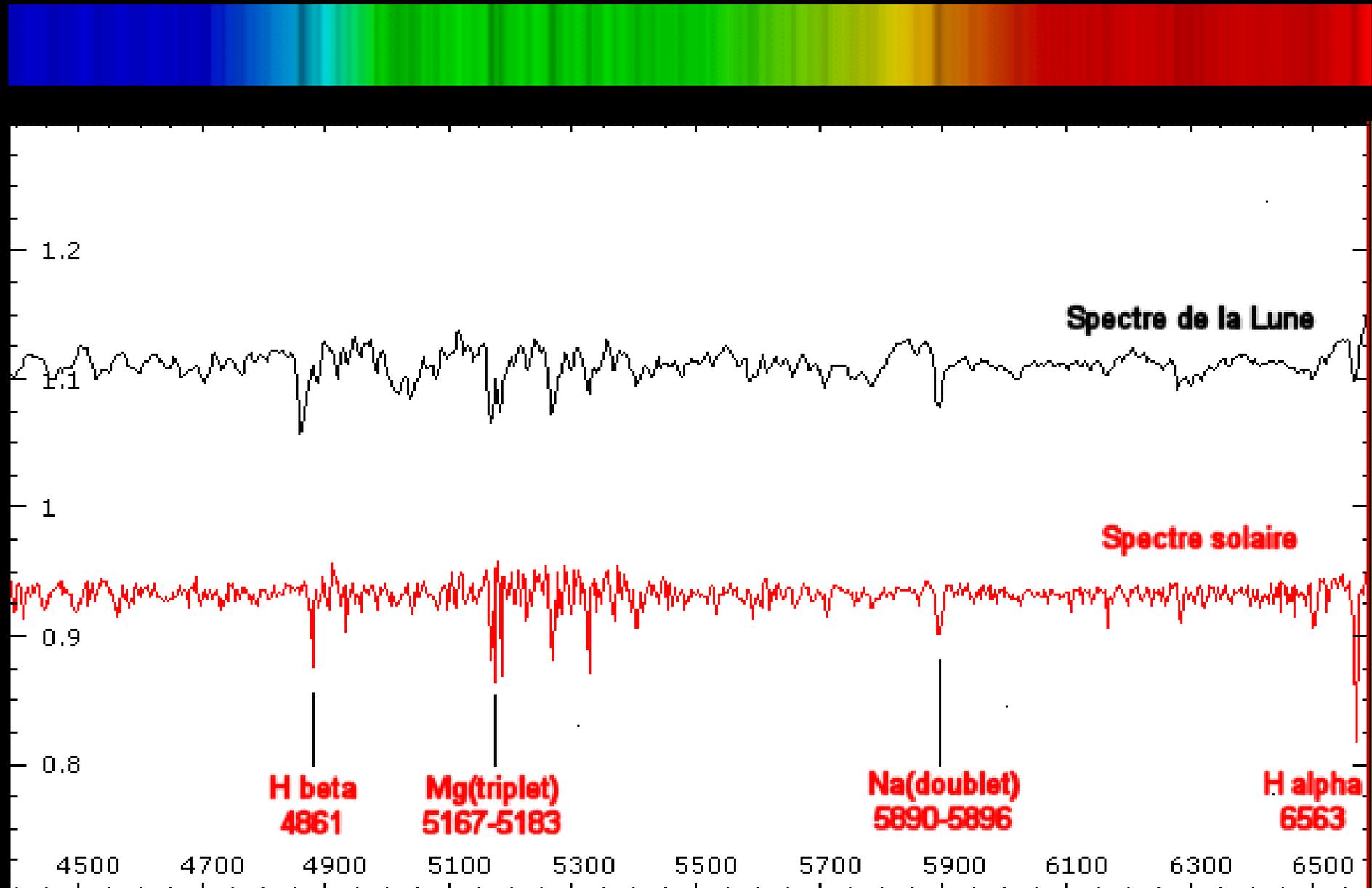
ETALONNAGE D'UN SPECTRE



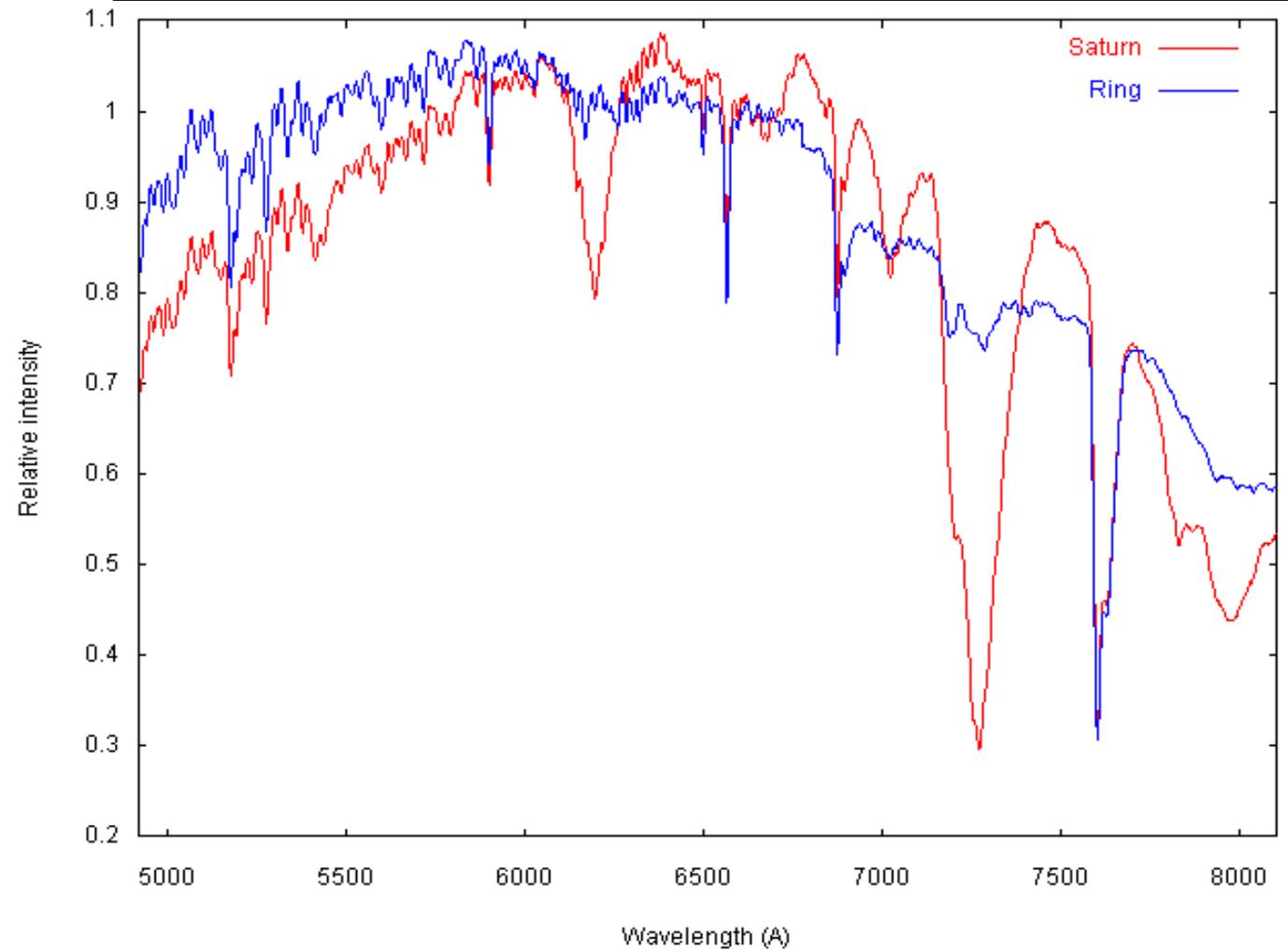
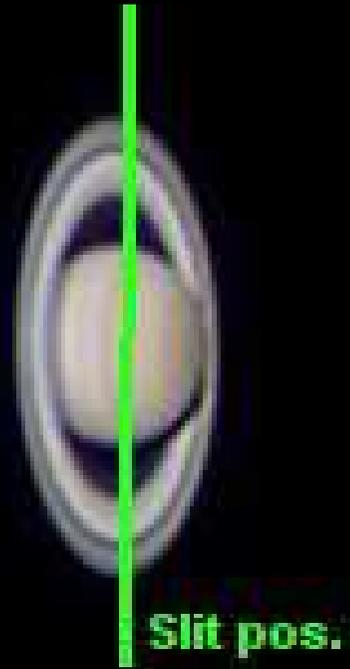
Etoile de type solaire 49 Vi



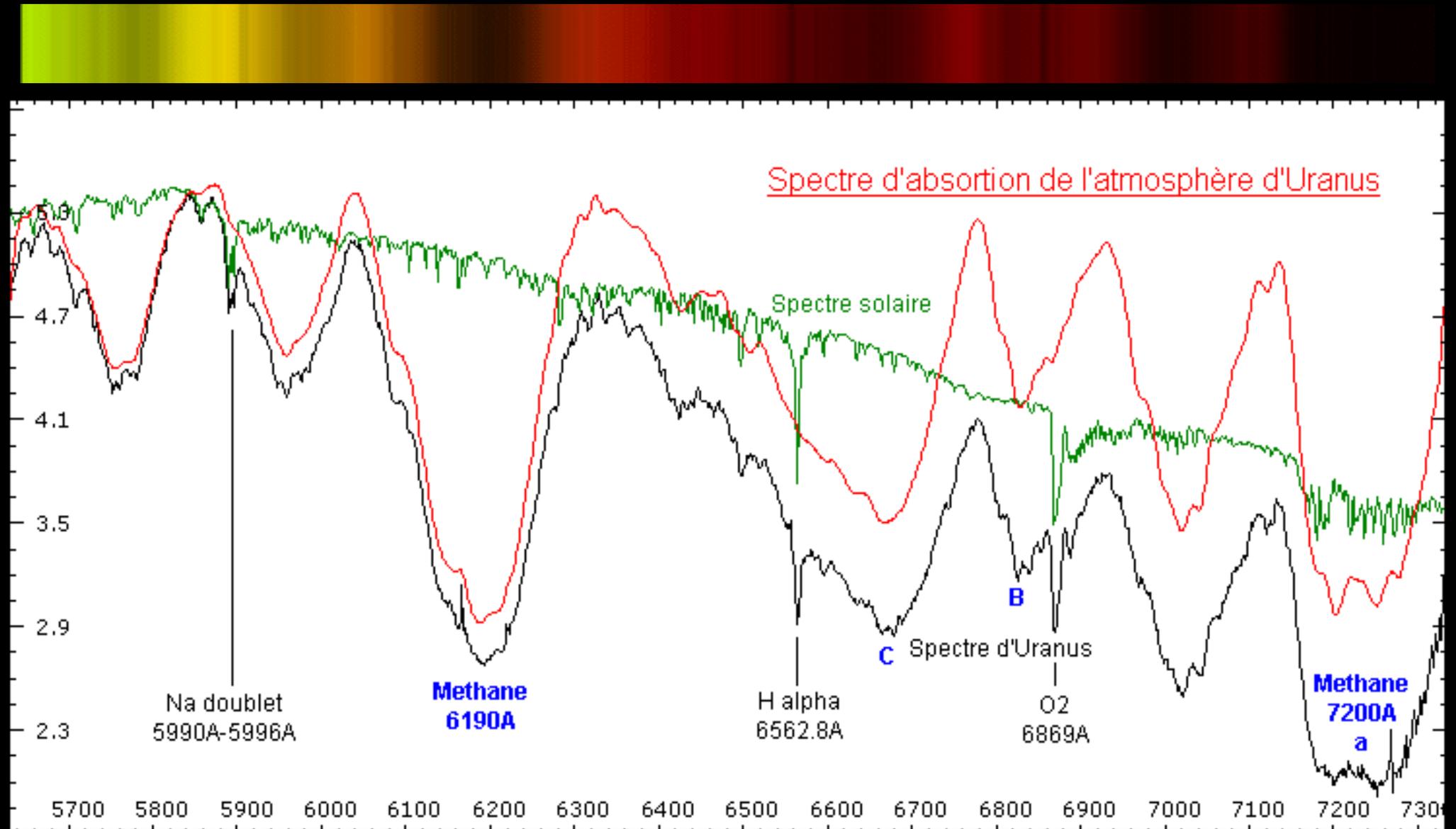
Spectre de la Lune



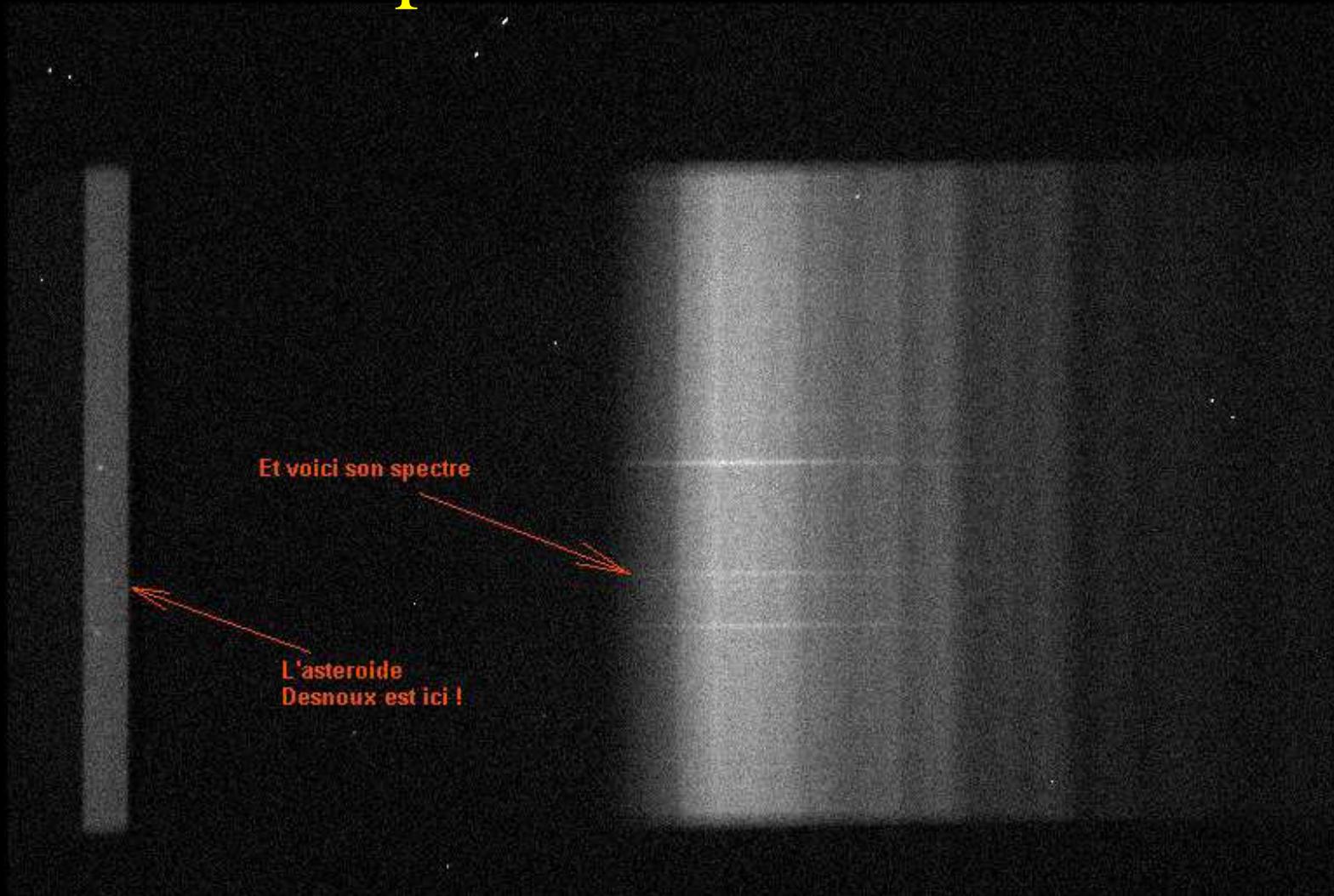
Spectre planétaire



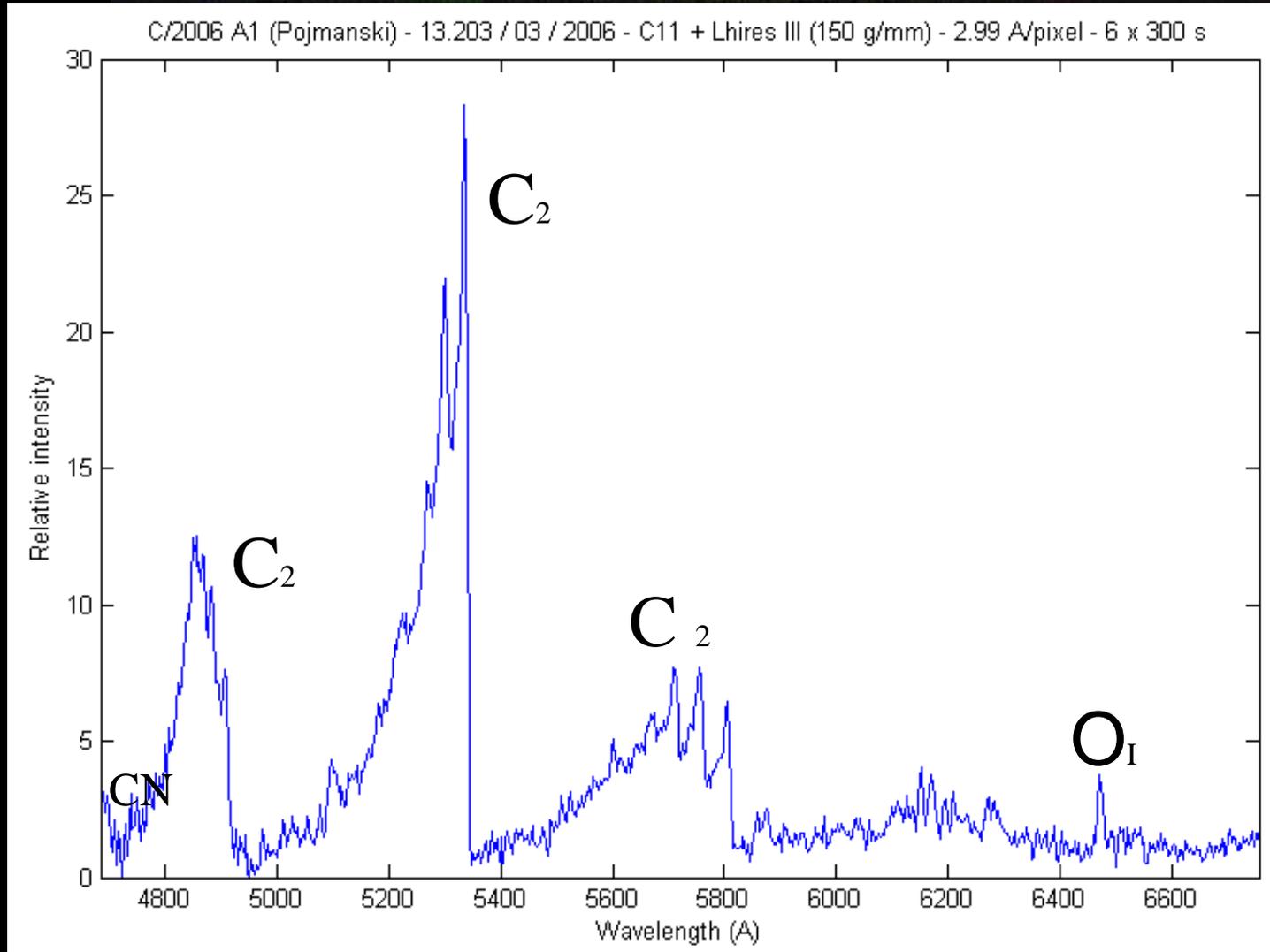
Spectre de la planète Uranus



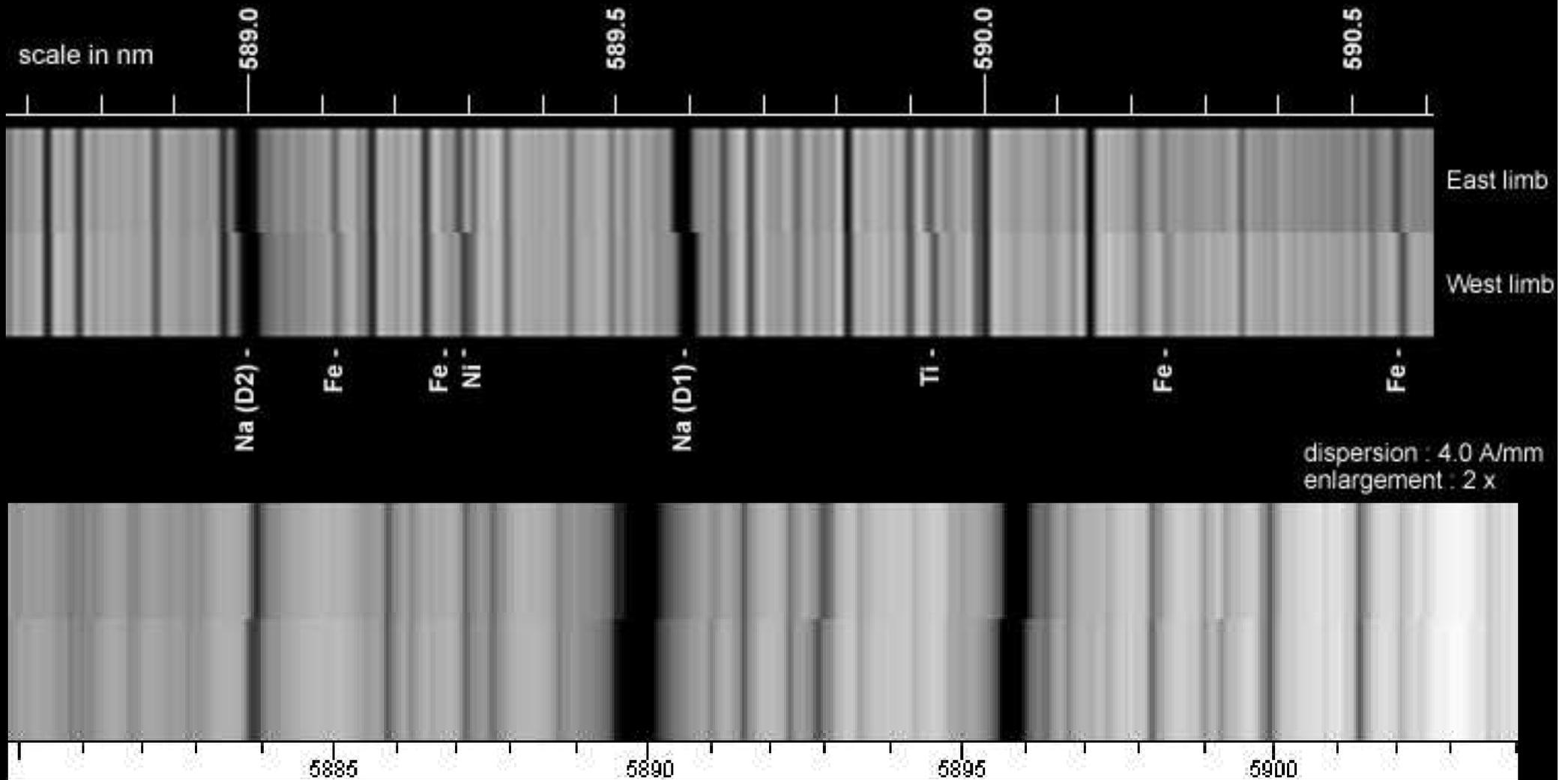
Spectre d'un astéroïde



Spectre de la comète Pojmanski

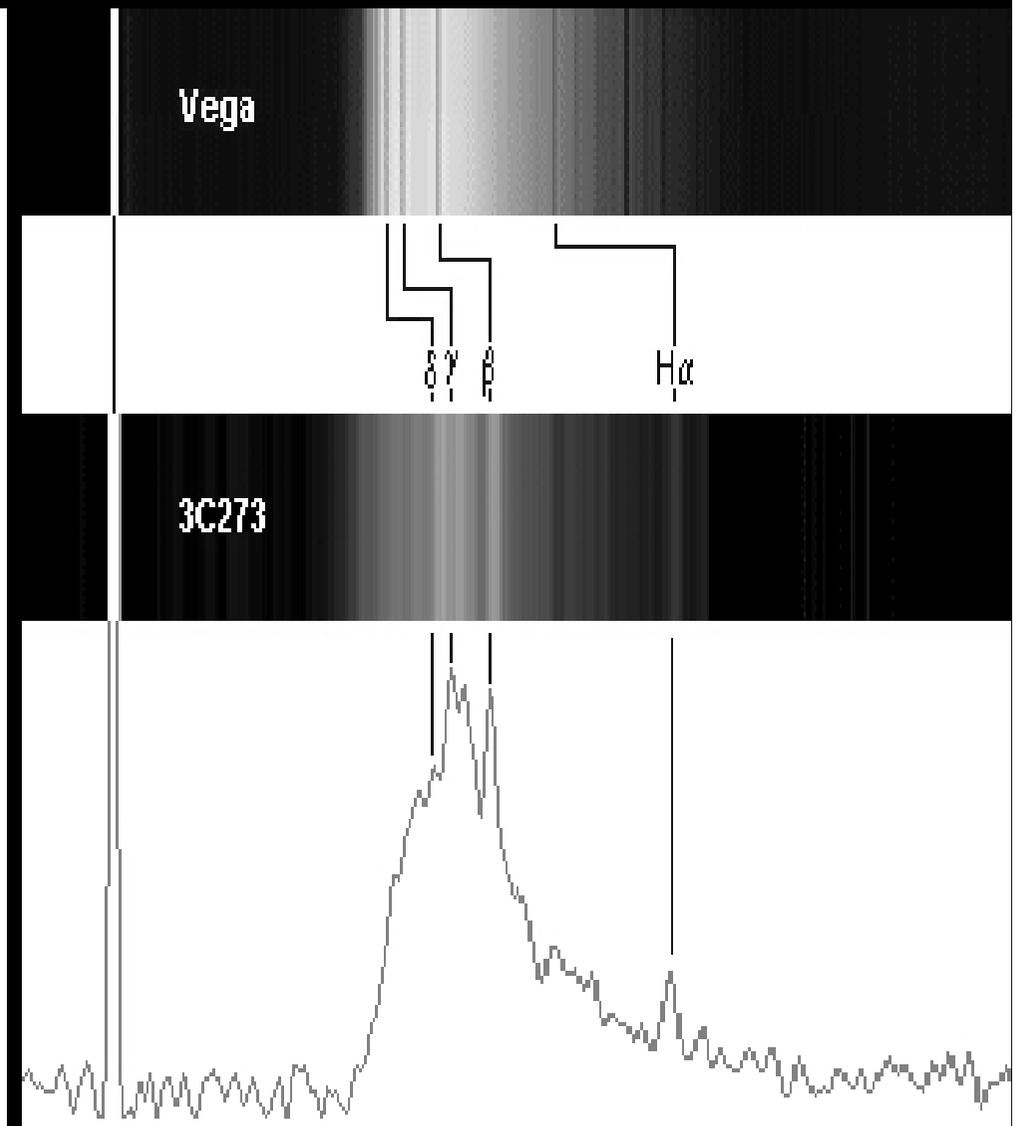
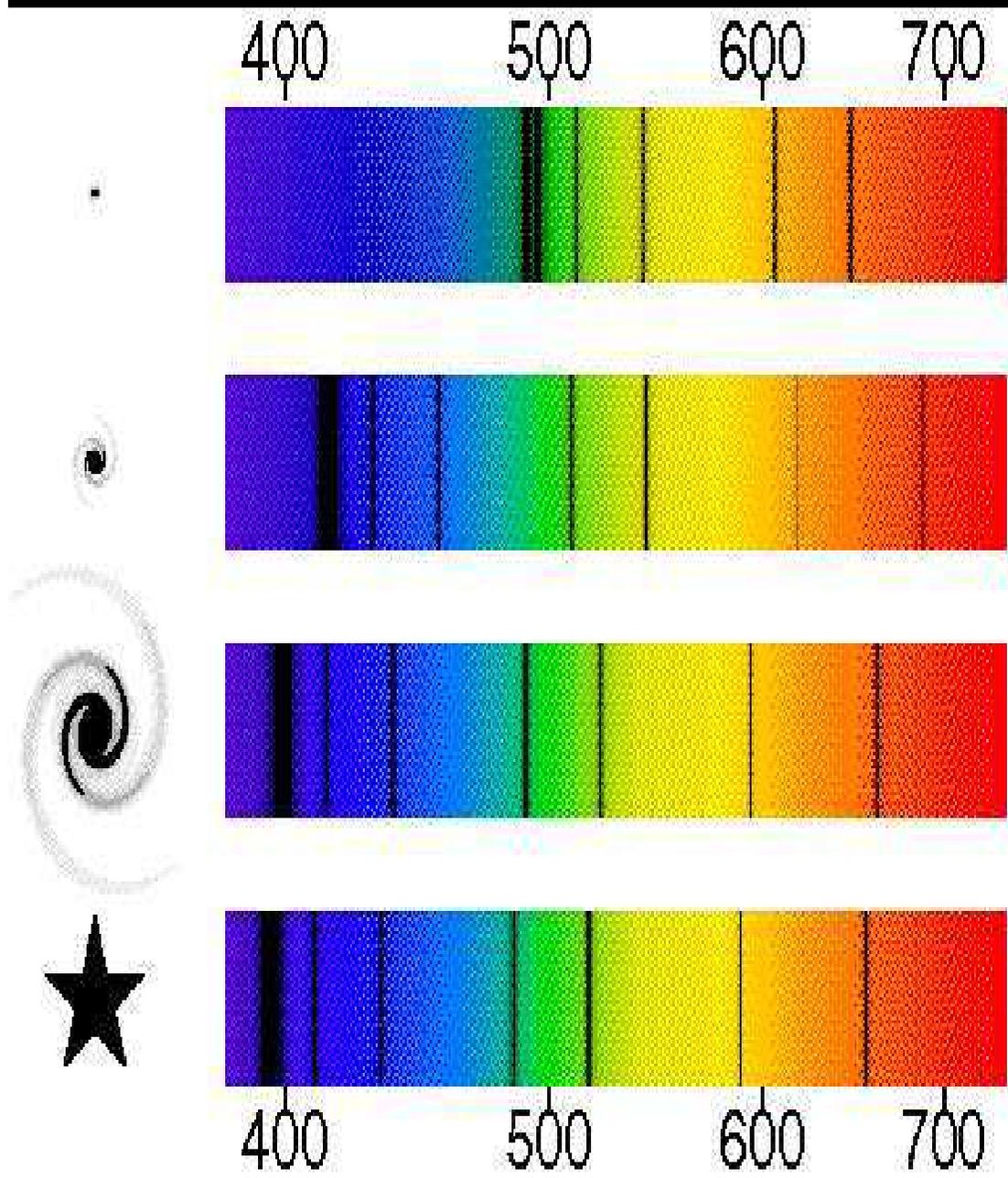


Effet de Rotation



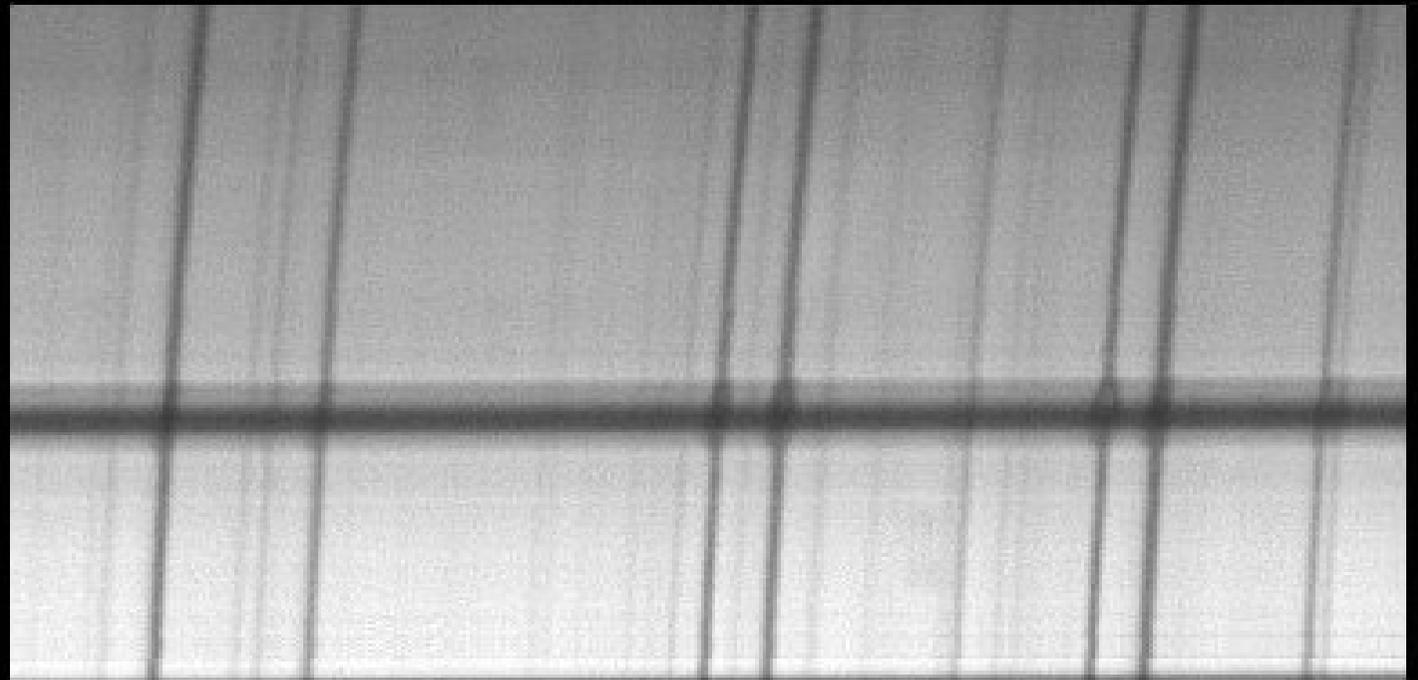
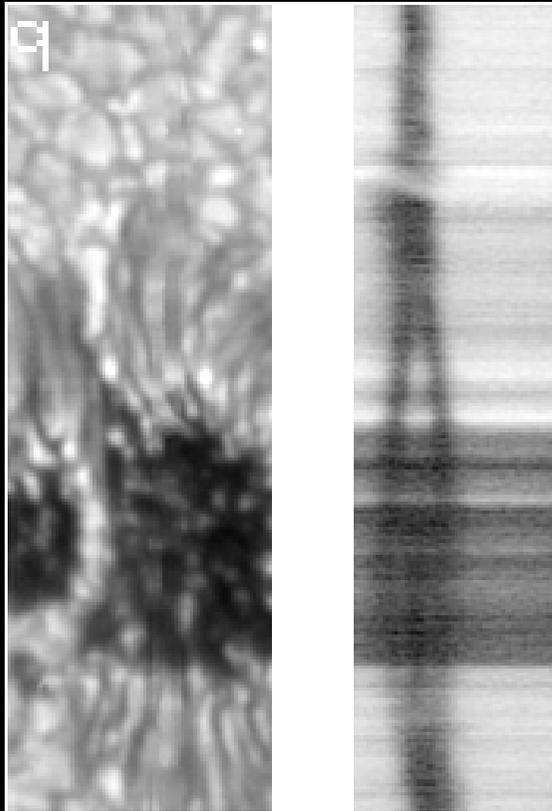
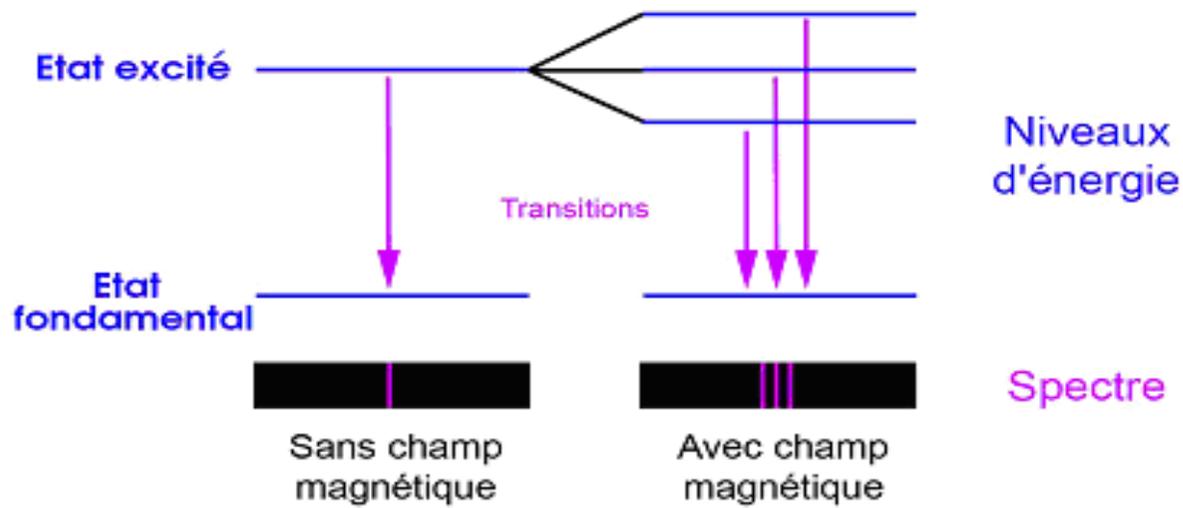
Doublet du Sodium ici spectre du Soleil

Décalage spectrale effet Doppler/ Fizeau



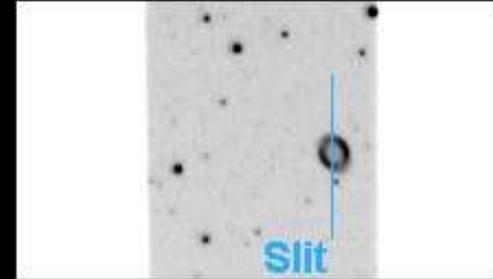
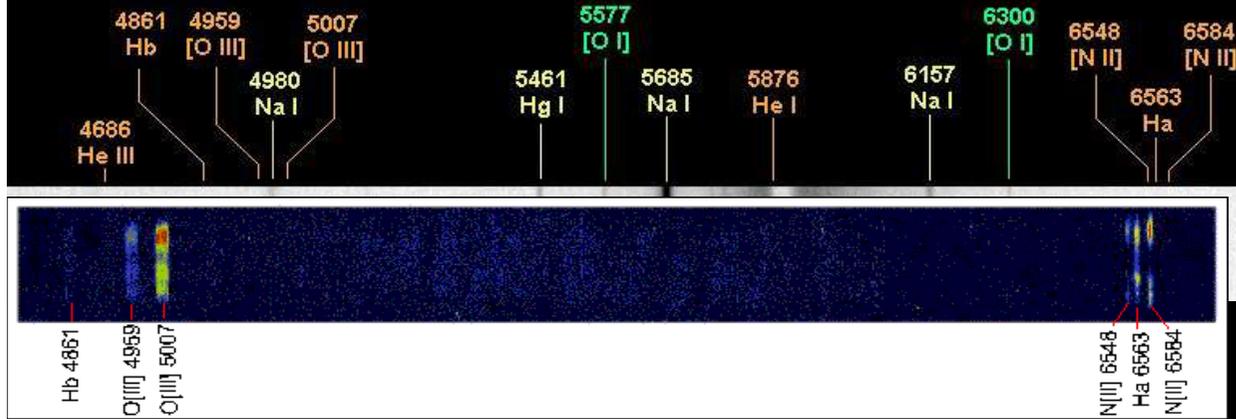
$$\frac{\lambda' - \lambda}{\lambda} = \frac{\Delta\lambda}{\lambda} = \pm \frac{v}{c} \quad (4)$$

Effet Zeeman

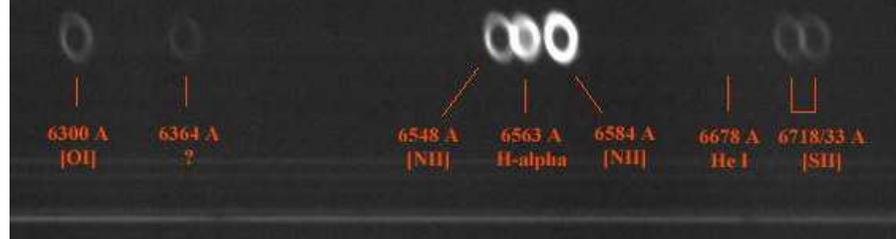
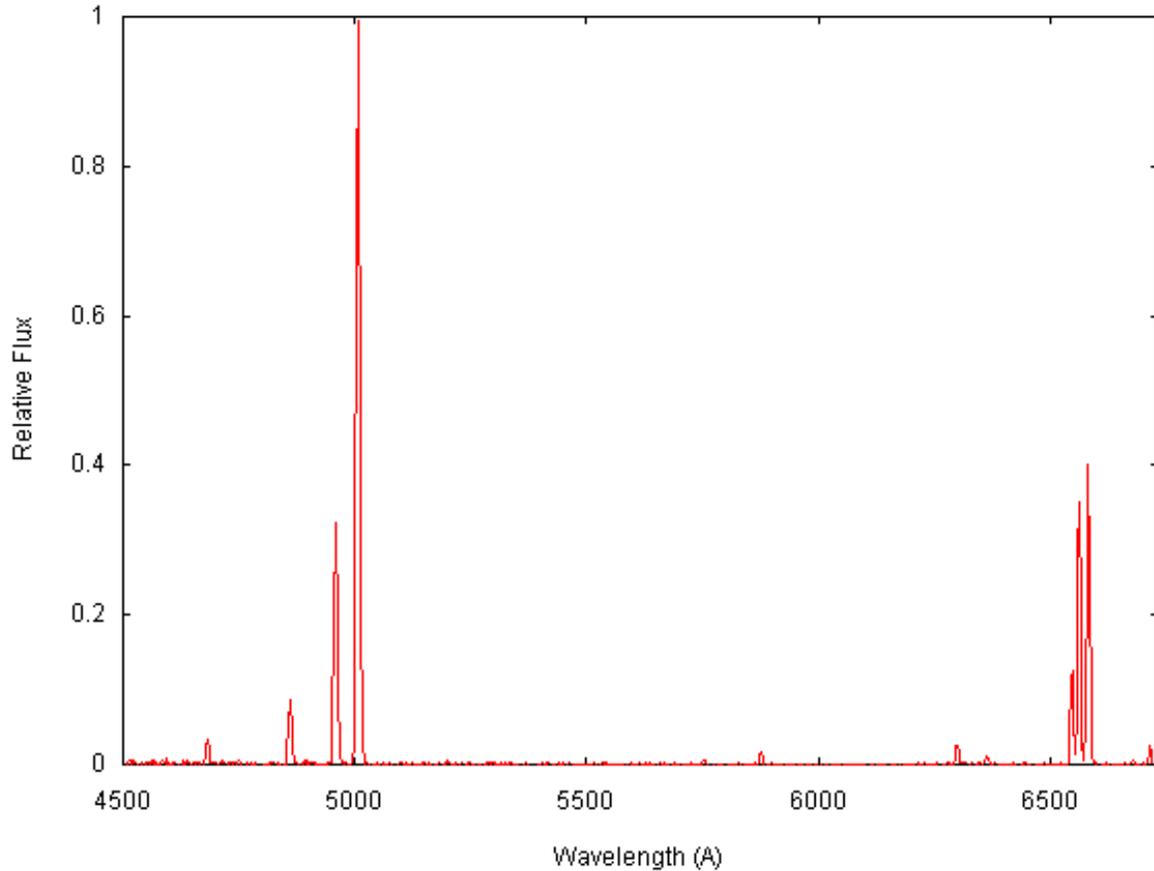


Zeeman effect by sunspot's magnetic field

Spectre d'une nébuleuse planétaire M 57



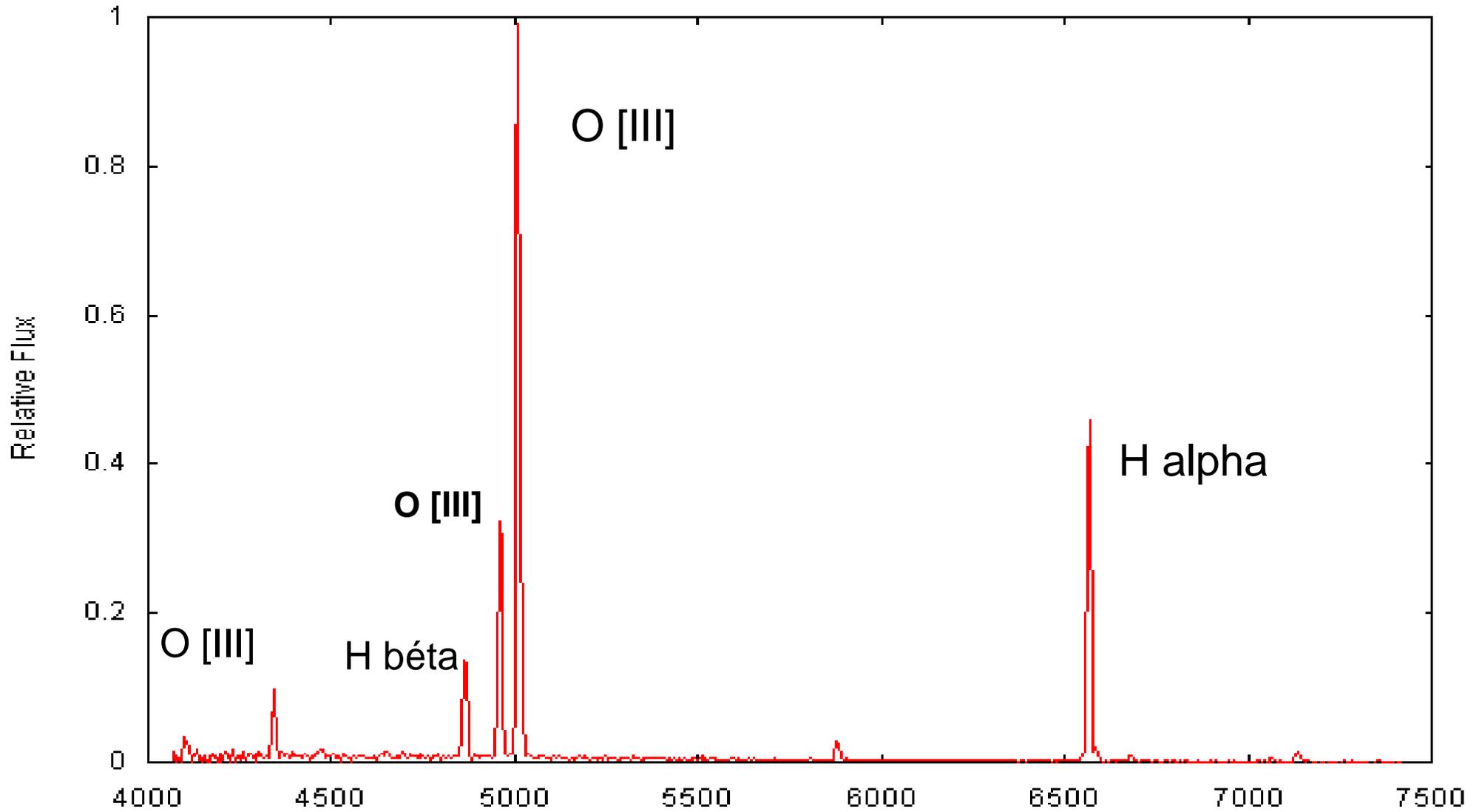
M57 - 4.89 / 08 / 2002 - FS128 refractor - 18 x 120 s - 2.882 Å/pixel



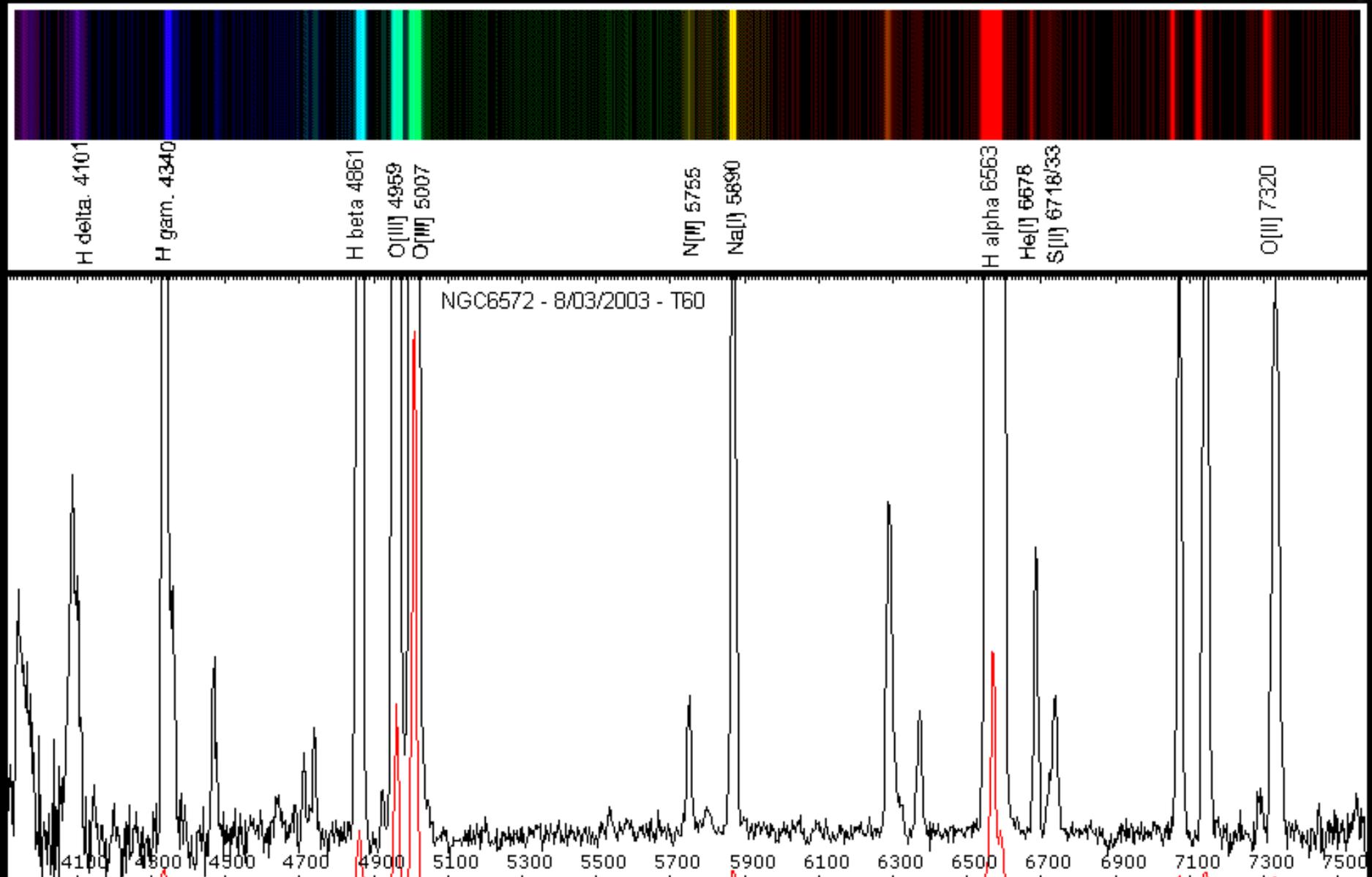
Spectre Nébuleuse planétaire NGC 6826



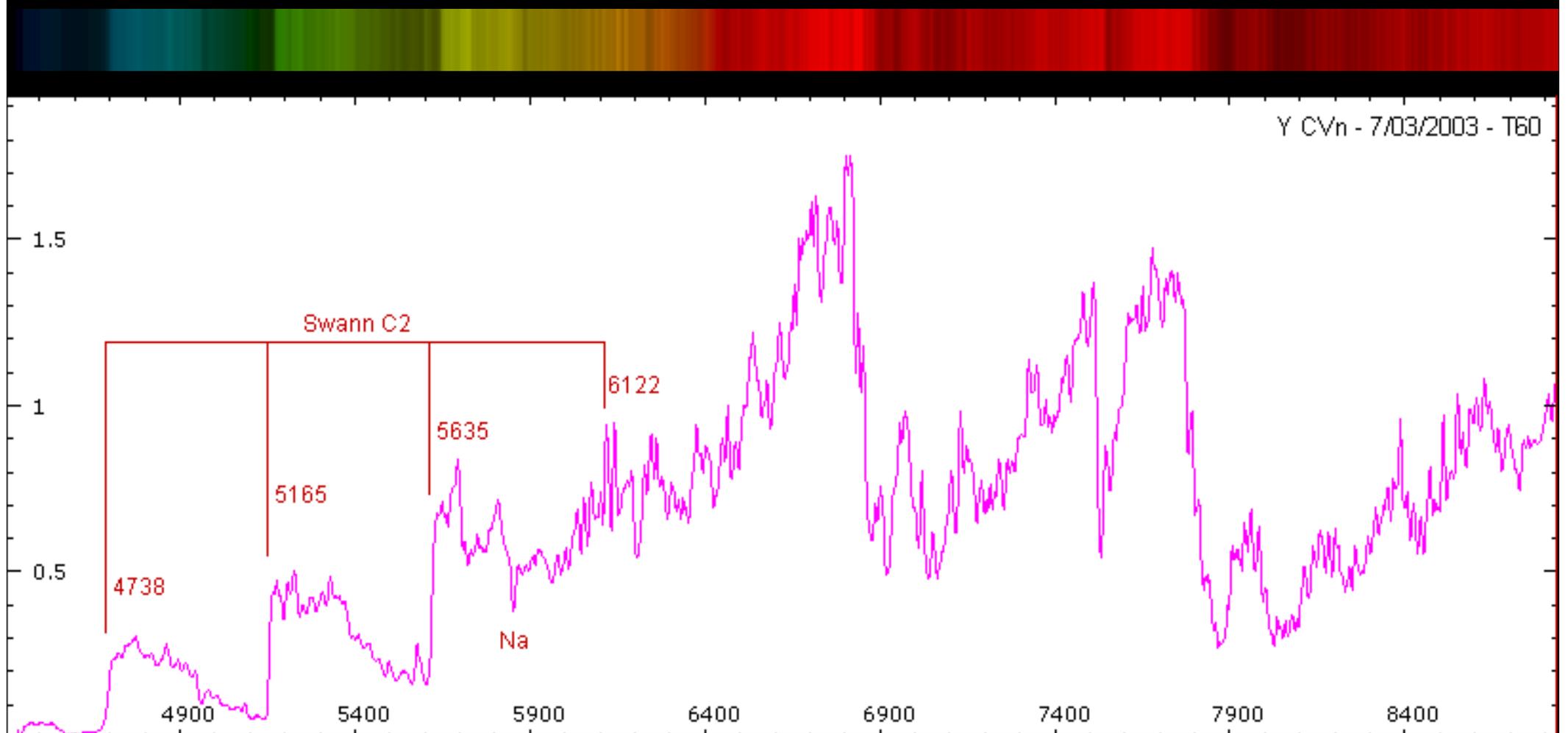
NGC 6826 - 19.94 / 07 / 2002 - T60 Pic du Midi - 15 x 30 s - 5.74 Å/pixel



Spectre de la nébuleuse planétaire NGC 6572 (nébuleuse de l'Émeraude)



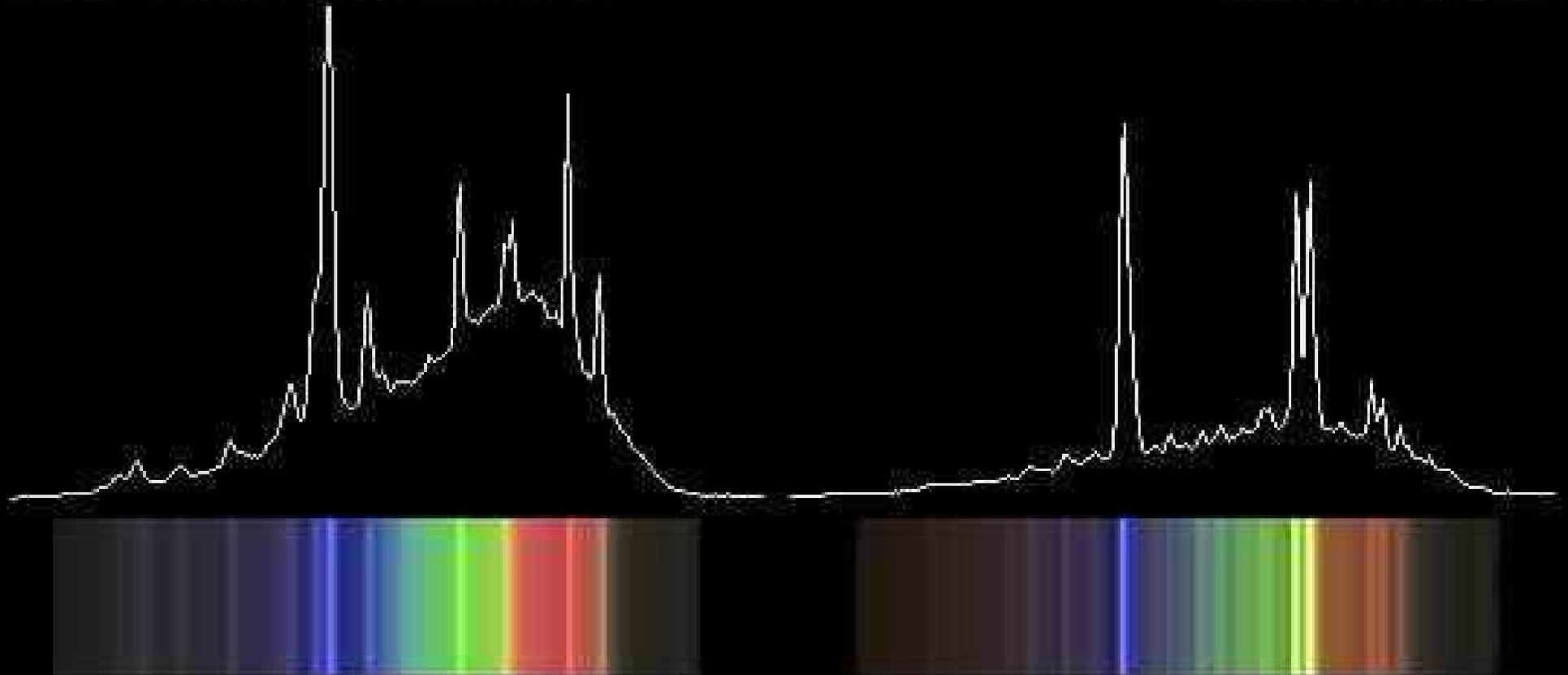
Y CVn Etoile de type carbonée



Spectres d'étoiles massives de type Wolf-Rayet

Colorful emission line stars in Cygnus...

100772.47@compuserve.com

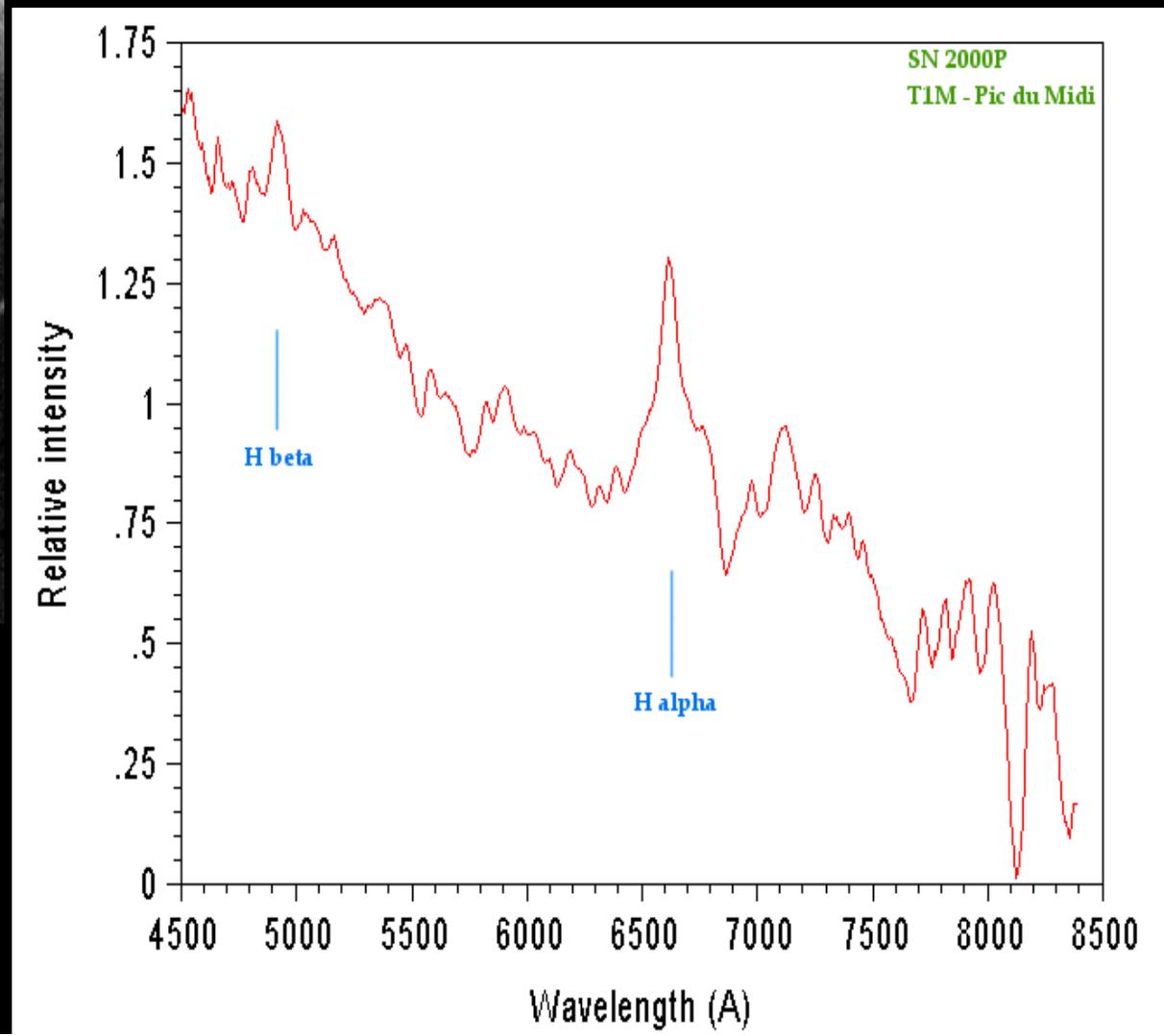
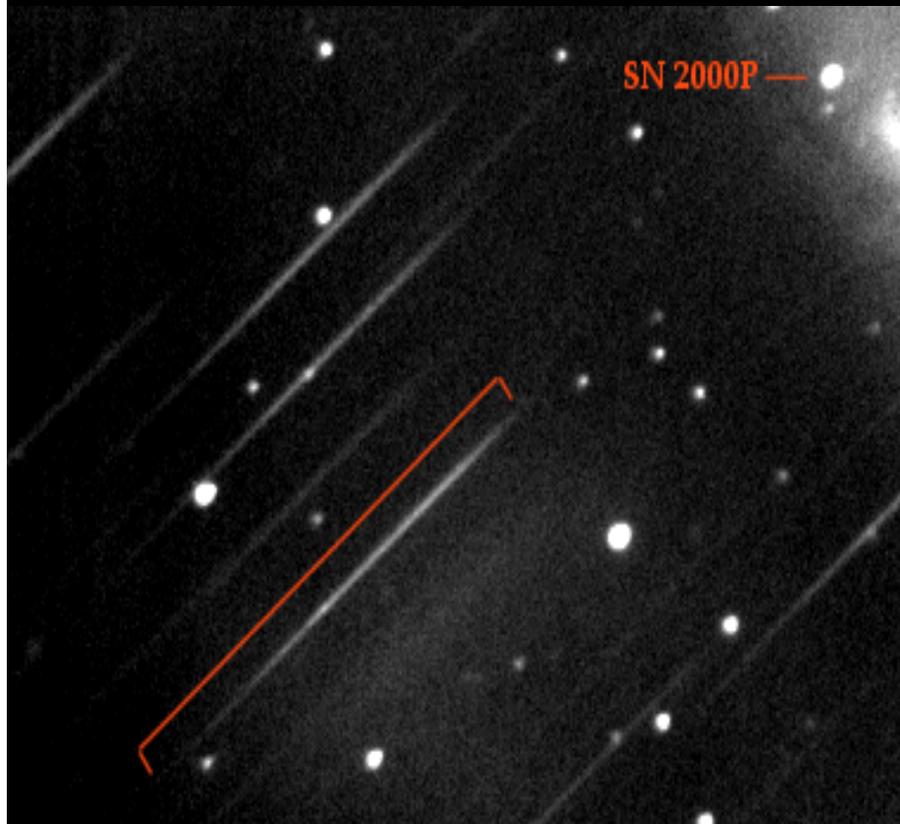


WR 136 - spec type WN6b(h) = nitrogen star

WR 135 - spec type WC8 = carbon star

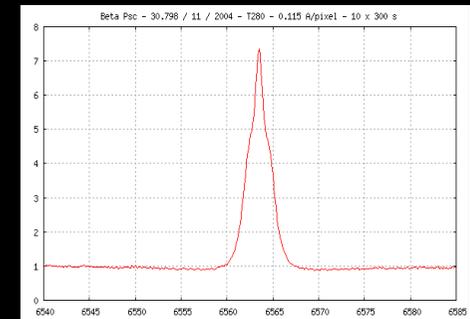
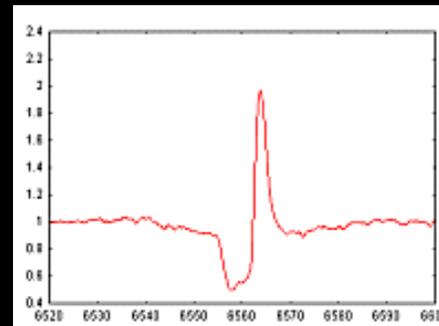
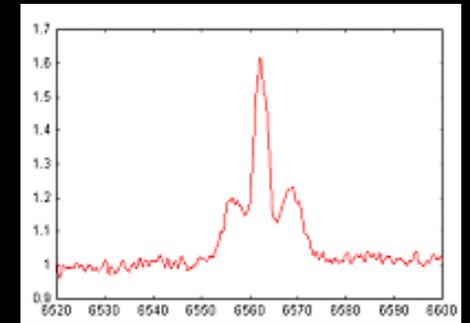
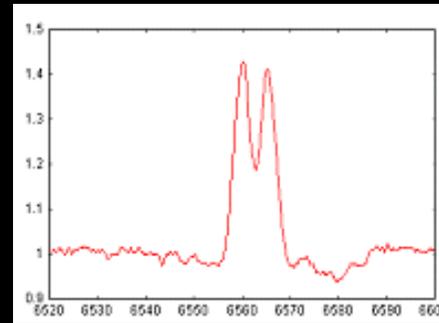
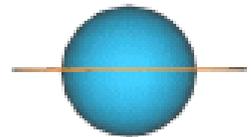
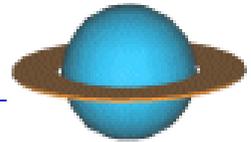
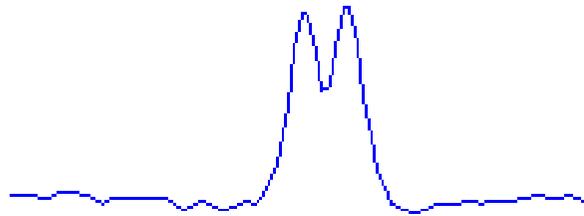
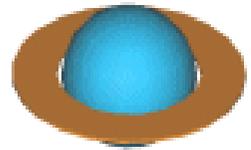
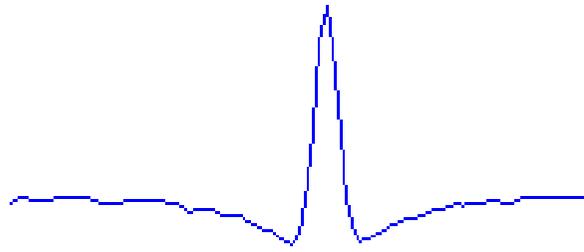
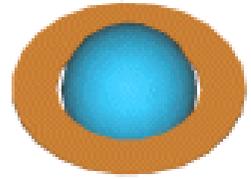
[c] Maurice Gavin - 1998 Oct 18 - Worcester Park Observatory - Surrey - UK 30cm Meade LX200+mk1a spectroscope+MX5-C CCD

Spectre de la supernova Sn 2000P de type II dans la galaxie NGC 4965



Spectres étoiles Be

Raie H alpha



MWC297 model

(slice through an edge-on view)

Star :

B1.5IVe 23700K
6R_o 10M_o
Rotational velocity = 400km/s

Accretion disc

Inner radius = 16 R_{*}
Outer radius = 50 AU
Opening angle = 5°
Accretion rate : $2 \cdot 10^{-5}$ M_o/year

Equatorial region (disc/wind interface):
Terminal velocity = 70km/s
Mass flux = $0.8 \cdot 10^{-9}$ M_o/year

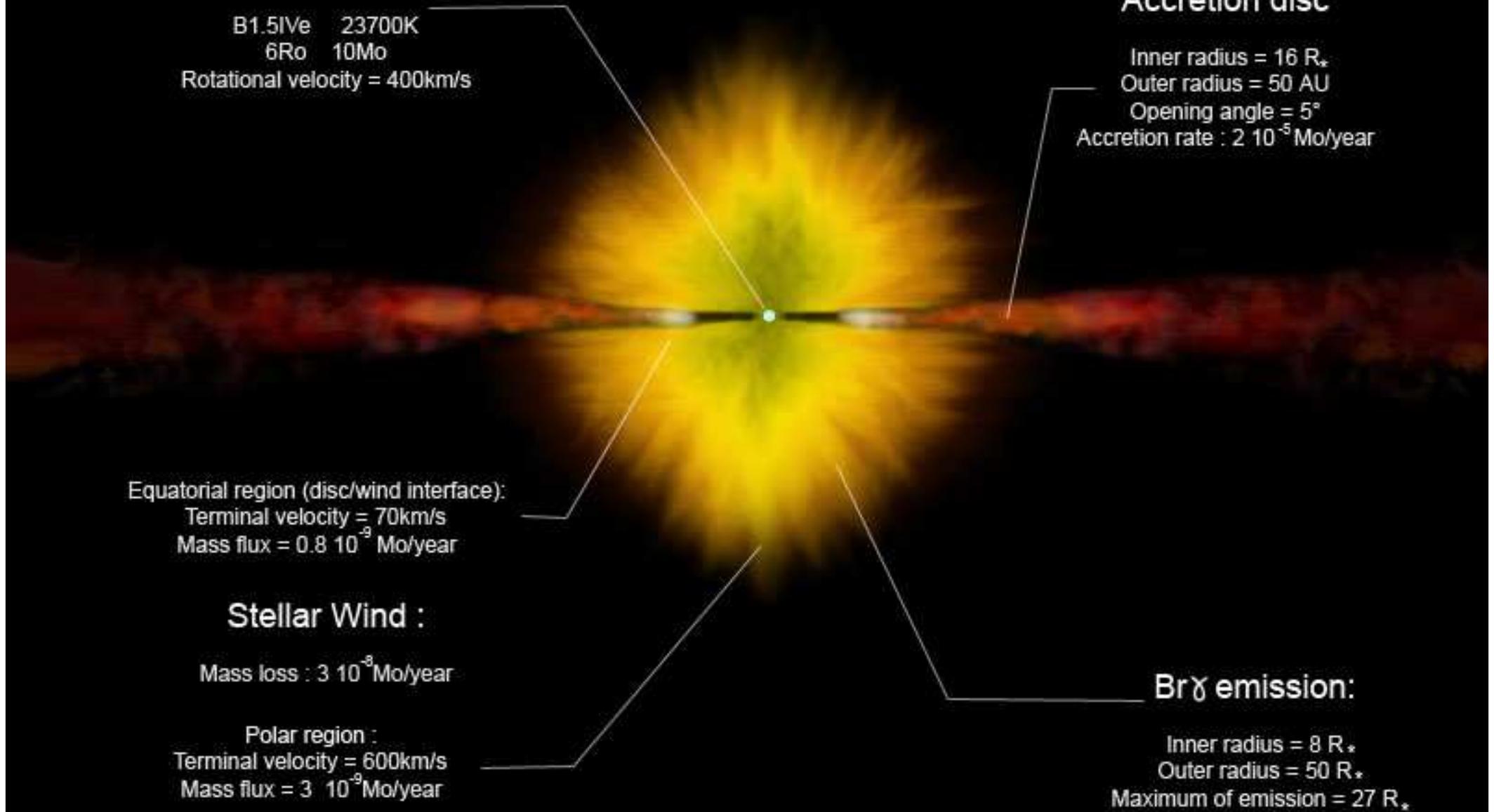
Stellar Wind :

Mass loss : $3 \cdot 10^{-8}$ M_o/year

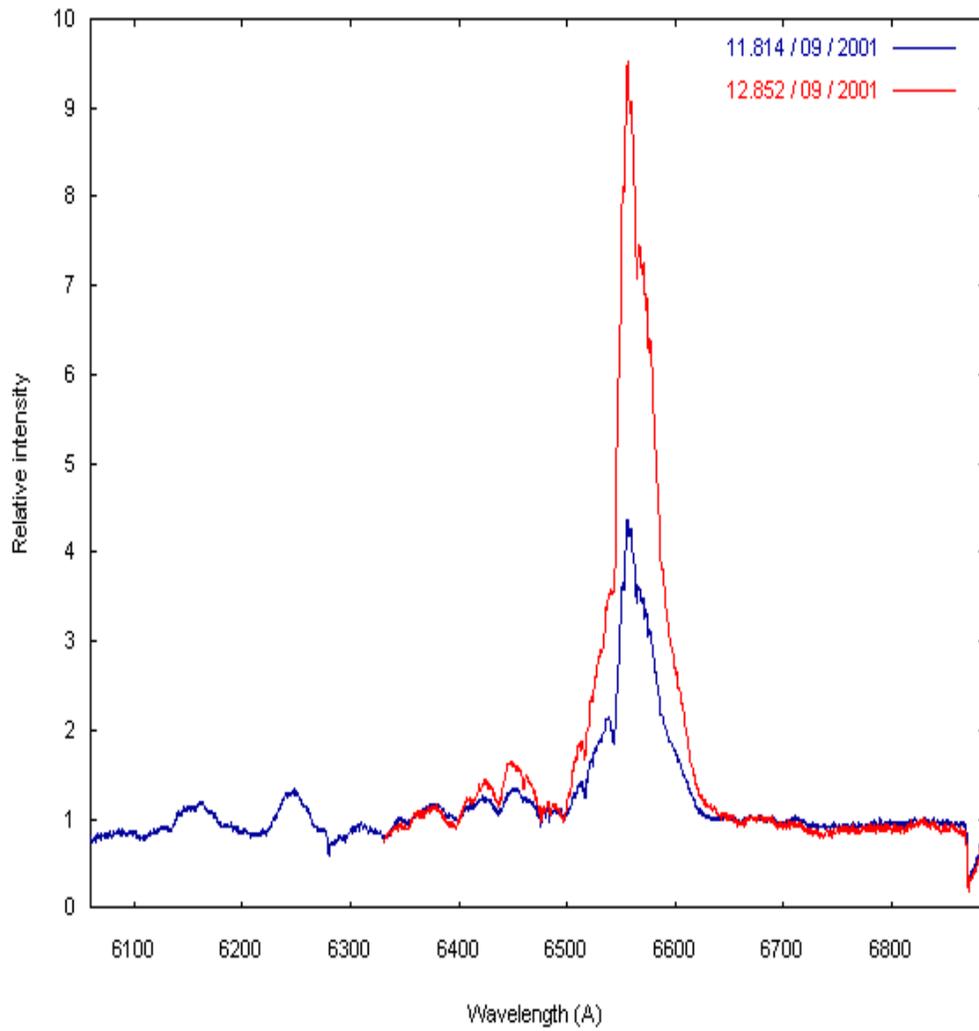
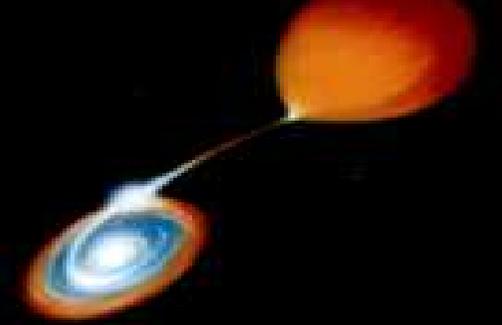
Polar region :
Terminal velocity = 600km/s
Mass flux = $3 \cdot 10^{-9}$ M_o/year

Br γ emission:

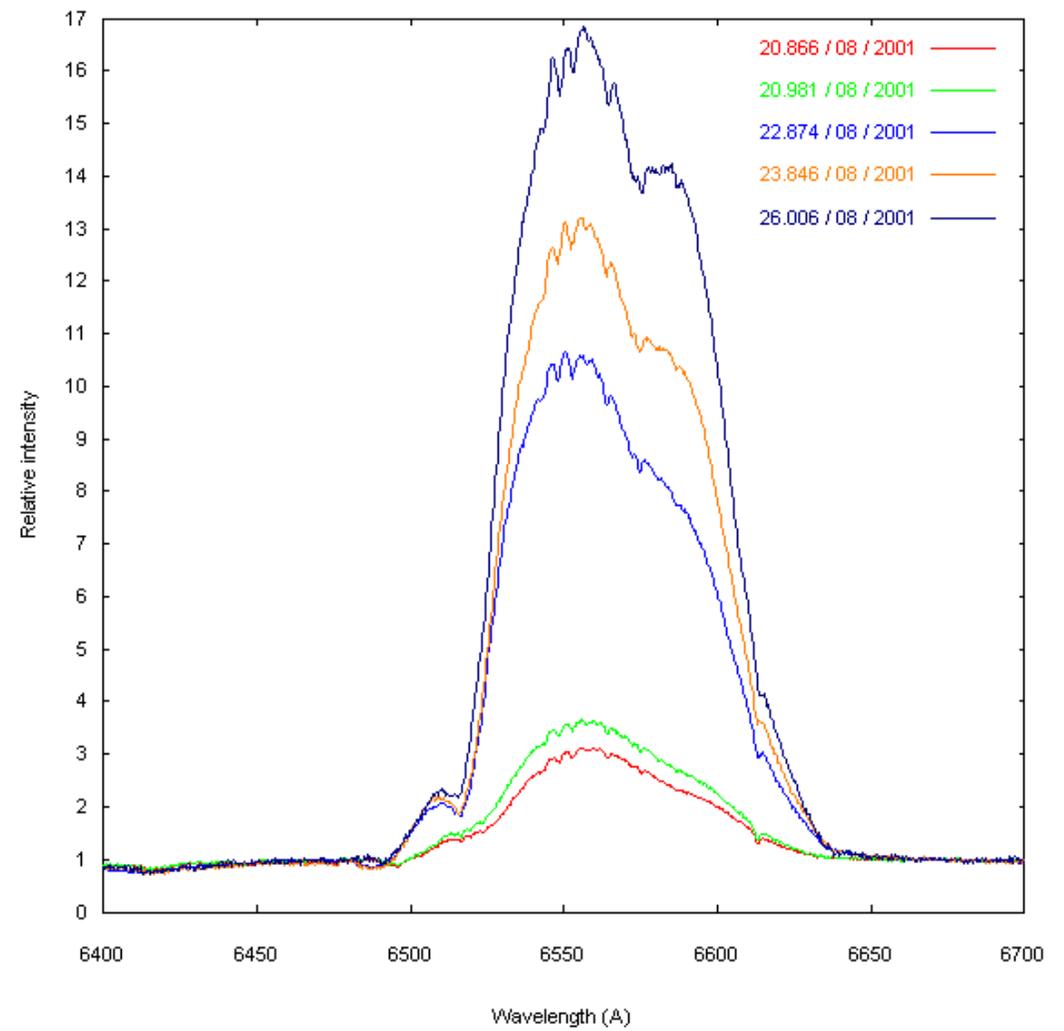
Inner radius = 8 R_{*}
Outer radius = 50 R_{*}
Maximum of emission = 27 R_{*}



Spectres de Novae



Nova V4740 Sgt



Nova V2275 Cygni