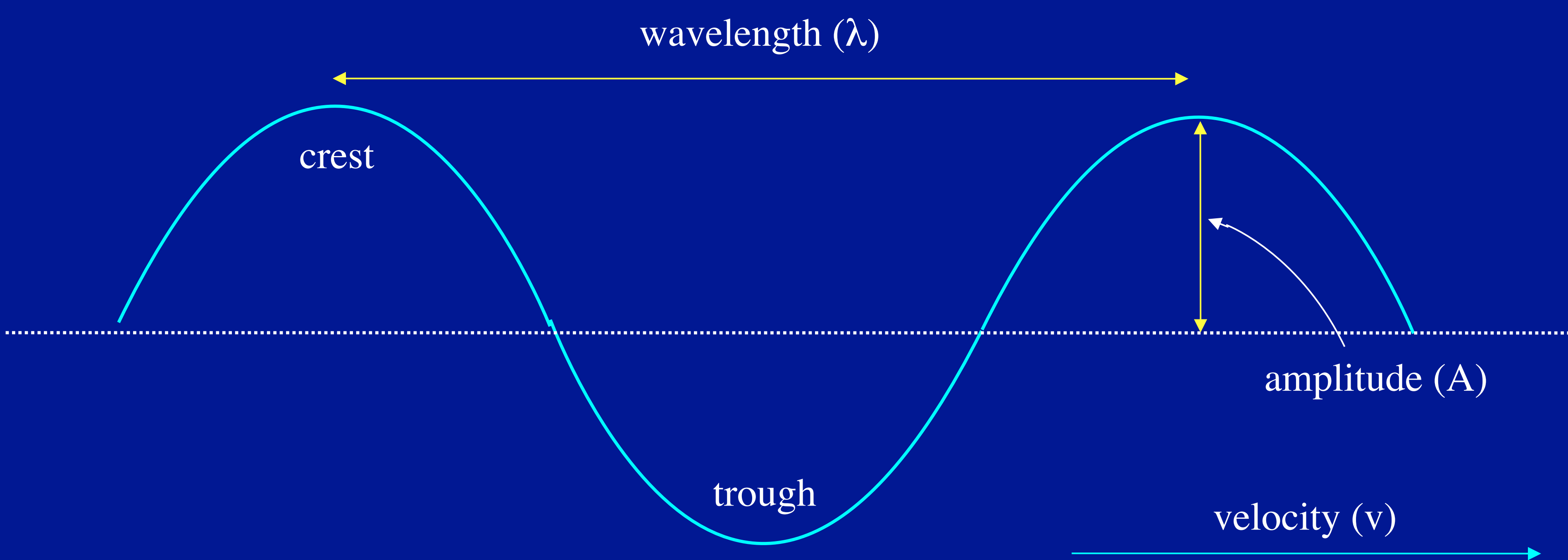
Review: Properties of a wave

Radiation travels as waves.
Waves carry information and energy.



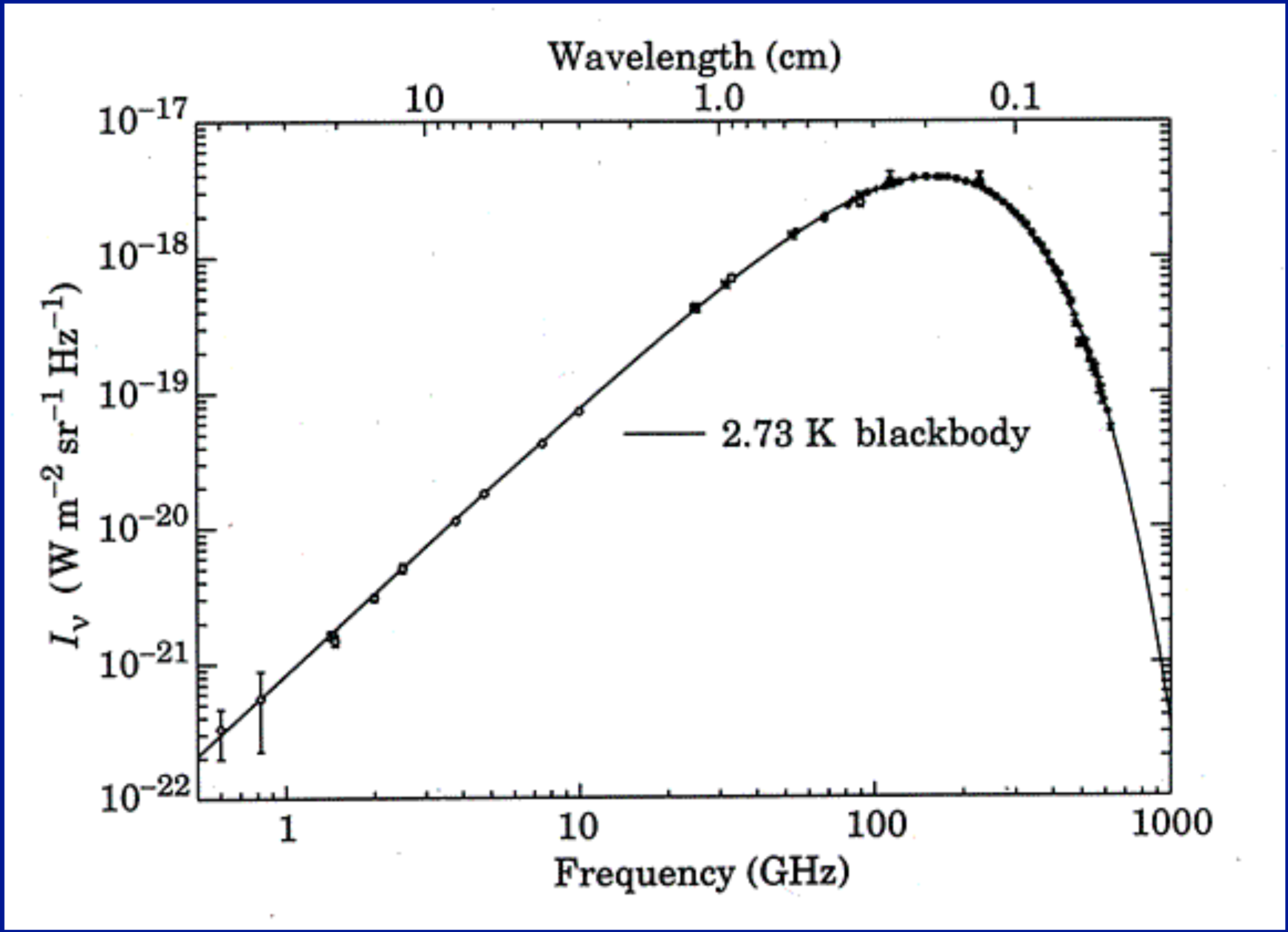
λ is a distance, so its units are m, cm, or mm, etc.

Period (T): time between crest (or trough) passages

Frequency (ν): rate of passage of crests (or troughs), $\nu = \frac{1}{T}$
(units: Hertz or cycles/sec)

EM waves:
$c = \lambda \nu$

Example: Blackbody - the microwave background



Clicker Question:

Compared to sound waves, radio waves travel:

A: faster

B: slower

C: at the same speed

Clicker Question:

Compared to radio waves, X-rays travel:

A: faster

B: slower

C: at the same speed

Clicker Question:

Electromagnetic radiation penetrates the Earth's atmosphere at what wavelengths?:

A: at visible, ultraviolet, and gamma-ray wavelengths

B: at all wavelengths

C: only at infrared wavelengths

D: only at optical wavelengths

E: at radio, visible, and part of the infrared wavelengths

Spectroscopy and Atoms

How do you make a spectrum?

For light, separate white light into its colors using a glass prism or "diffraction grating". For radiation in general, spread out the radiation by wavelength (e.g car radio, satellite TV receiver).

How we know these things:

- Physical states of stars, gas clouds, e.g. temperature, density, pressure.

- Chemical make-up of stars, galaxies, gas clouds

- Ages of stars and galaxies

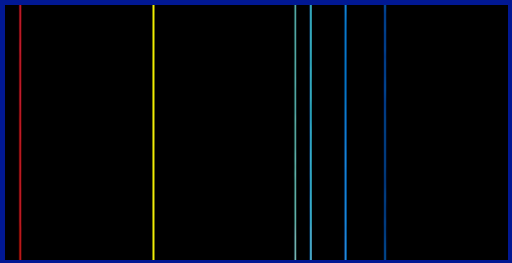
- Masses of stars, clouds, galaxies, extrasolar planets, rotation of galaxies, expansion of universe, acceleration of universe.

<u>All rely on taking and understanding spectra</u>

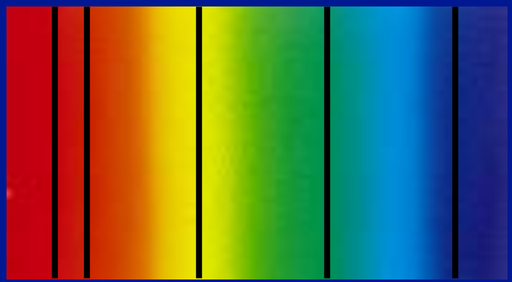
Types of Spectra

1. "Continuous" spectrum - radiation over a broad range of wavelengths (light: bright at every color).

2. "Emission line" spectrum - bright at specific wavelengths only.



3. Continuous spectrum with "absorption lines": bright over a broad range of wavelengths with a few dark lines.

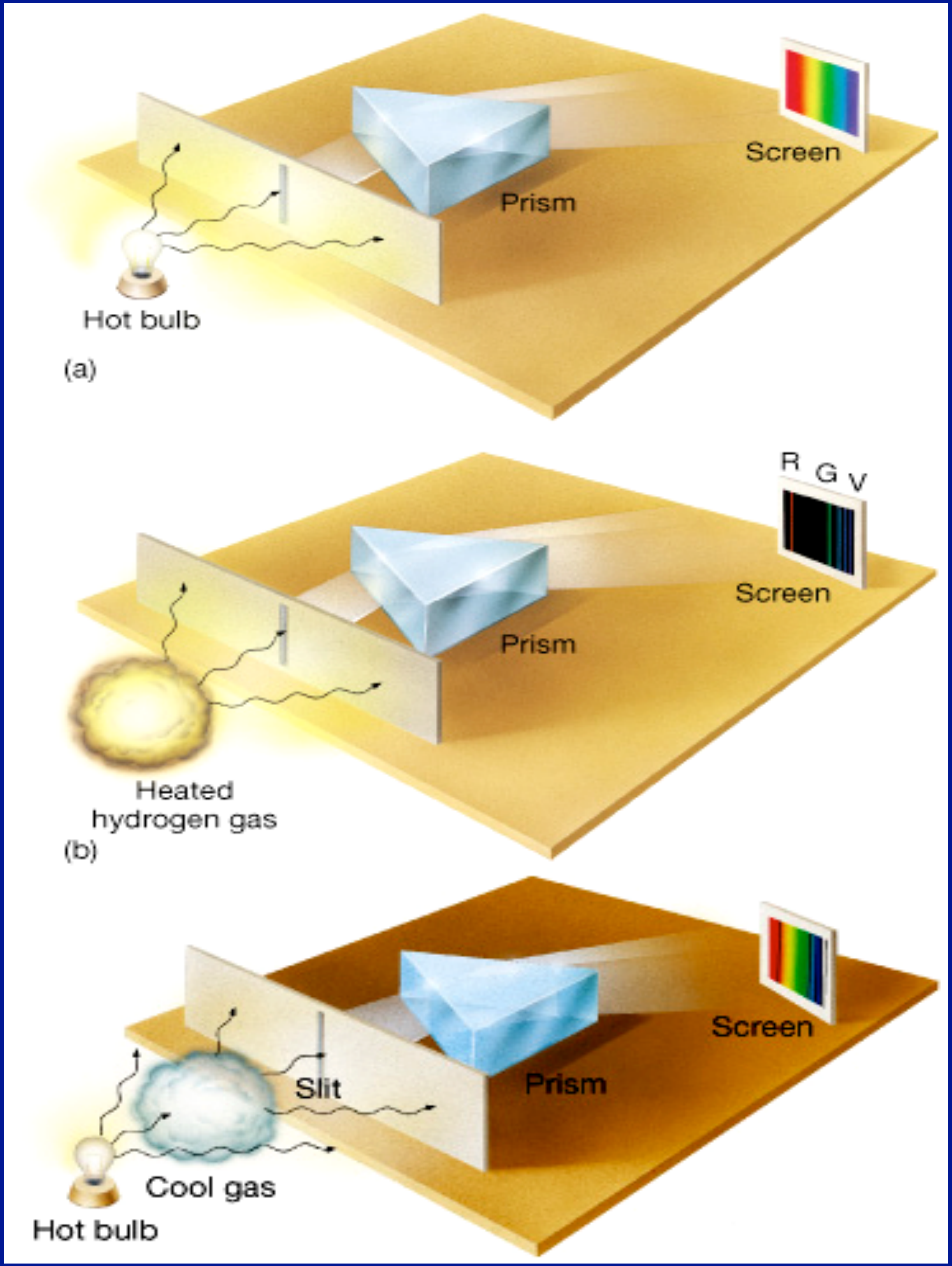


Kirchhoff's Laws

1. A hot, opaque solid, liquid or dense gas produces a continuous spectrum.

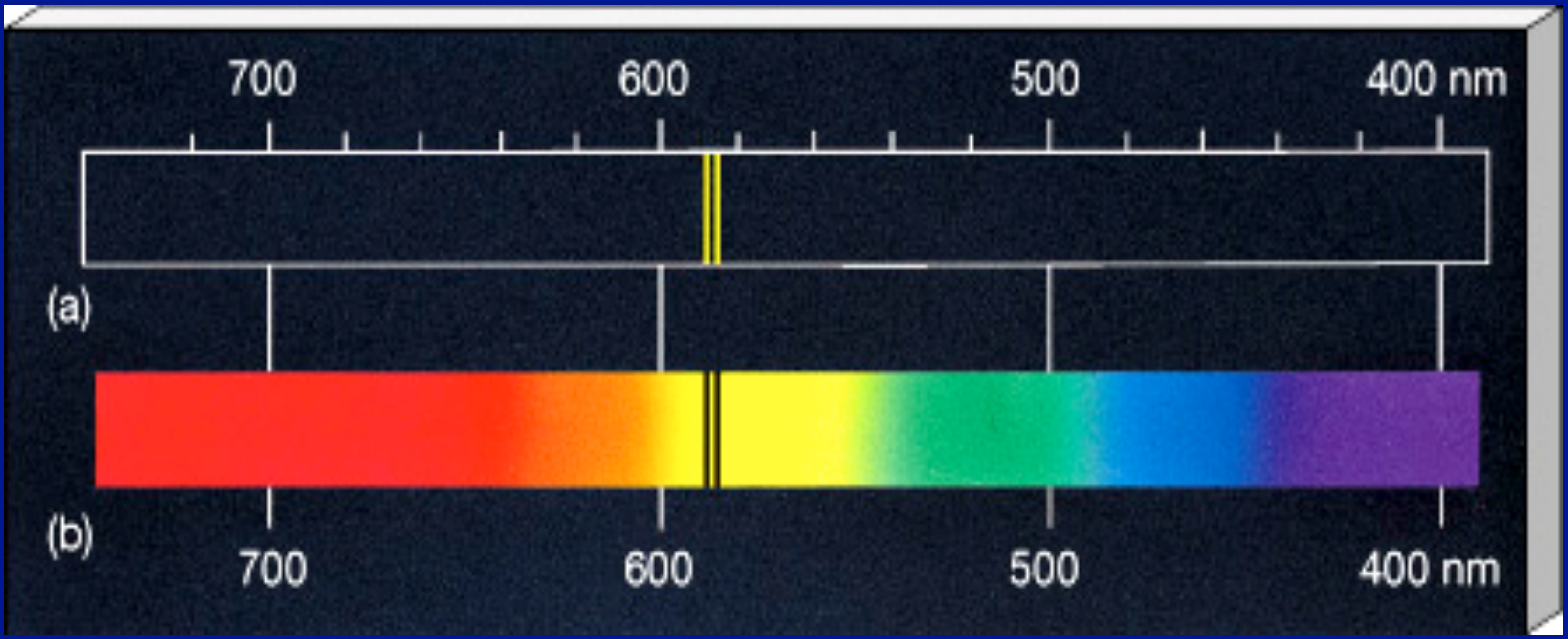
2. A transparent hot gas produces an emission line spectrum.

3. A transparent, cool gas absorbs wavelengths from a continuous spectrum, producing an absorption line spectrum.



The pattern of emission (or absorption) lines is a fingerprint of the element in the gas (such as hydrogen, neon, etc.)

For a given element, emission and absorption lines occur at the same wavlengths.

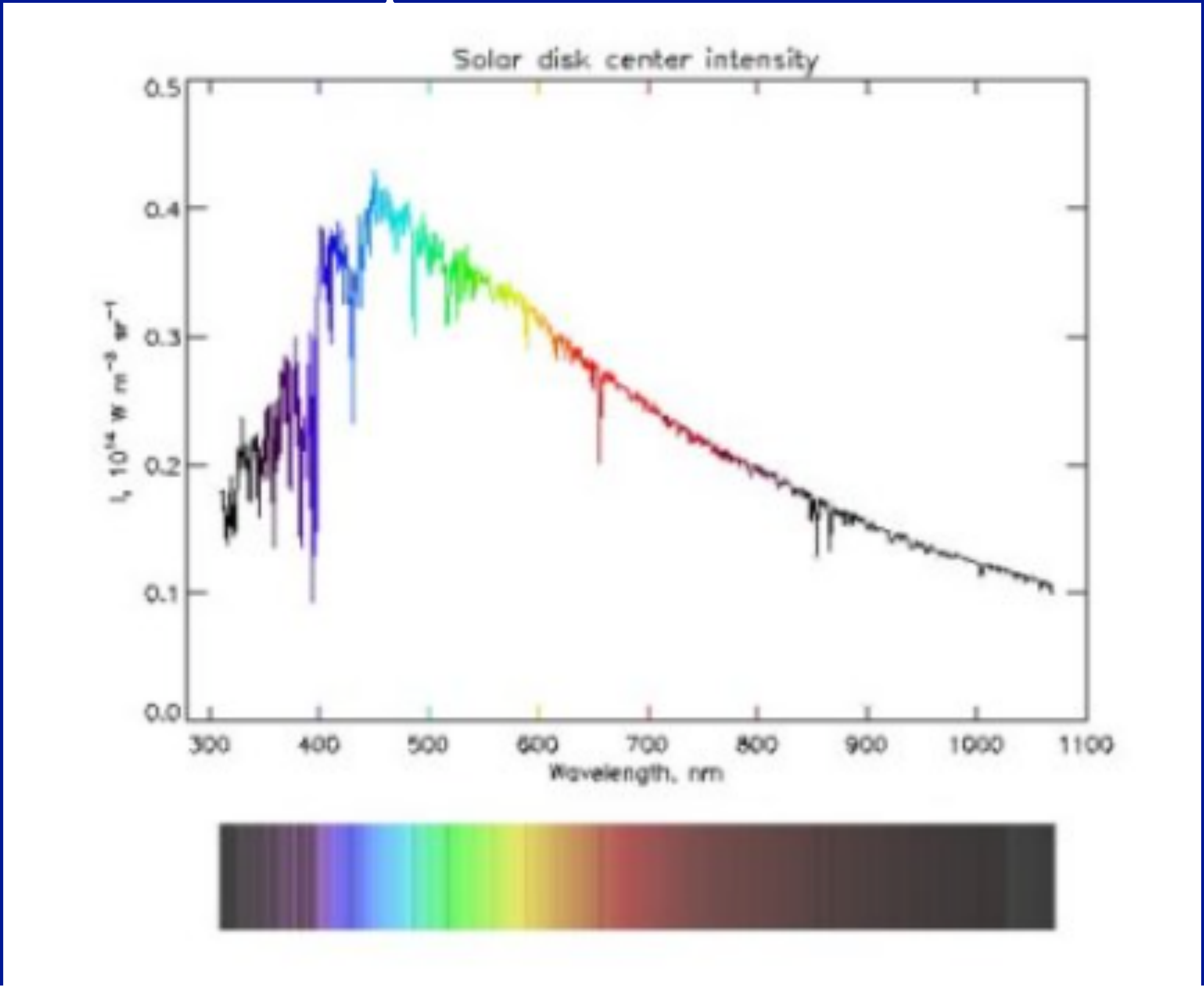


Sodium emission and absorption spectra

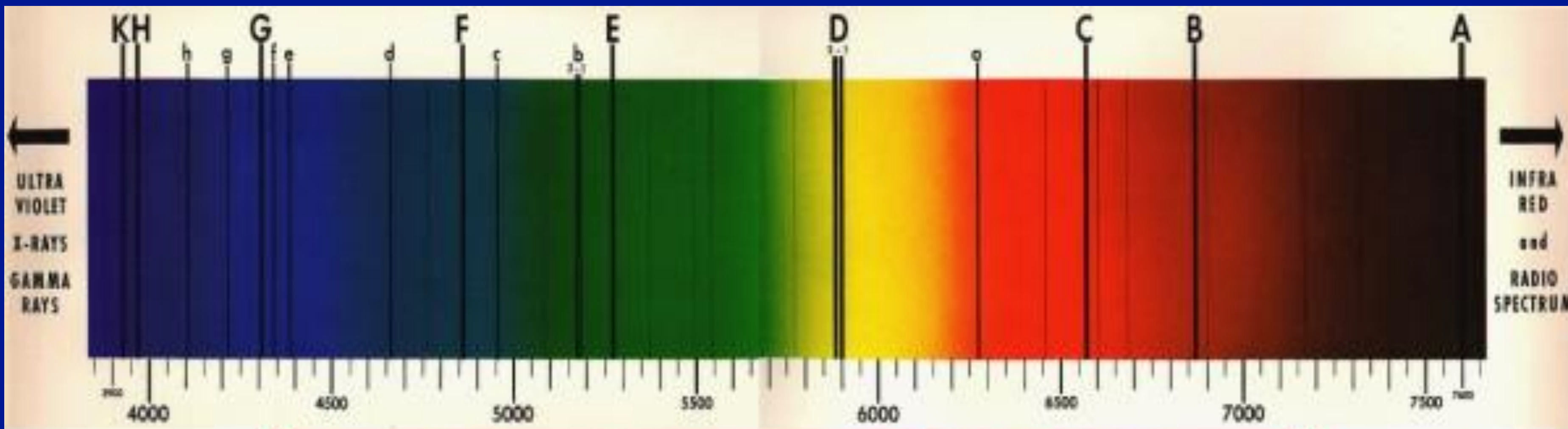
Demo - Spectra

Demo - Spectrum of the sun

Spectrum of the sun



Spectrum of the sun



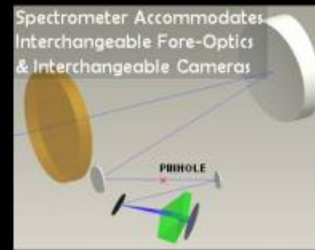
Legend of Absorption Lines in the Visible Solar Spectrum

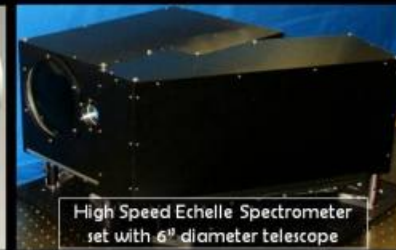
Letter	Wavelength (nm)	Chemical Origin	Colour Range
A	759.37	atmospheric O2	dark red
B	686.72	atmospheric O2	red
C	656.28	hydrogen alpha	red
D1	589.59	neutral sodium	red orange
D2	589.00	neutral sodium	yellow
E	526.96	neutral iron	green
F	486.13	hydrogen beta	cyan
G	431.42	CH molecule	blue
H	396.85	ionized calcium	darkviolet
K	393.37	ionized calcium	darkviolet

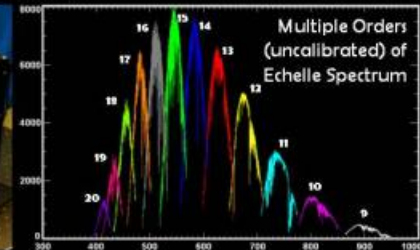
The Solar Spectrum

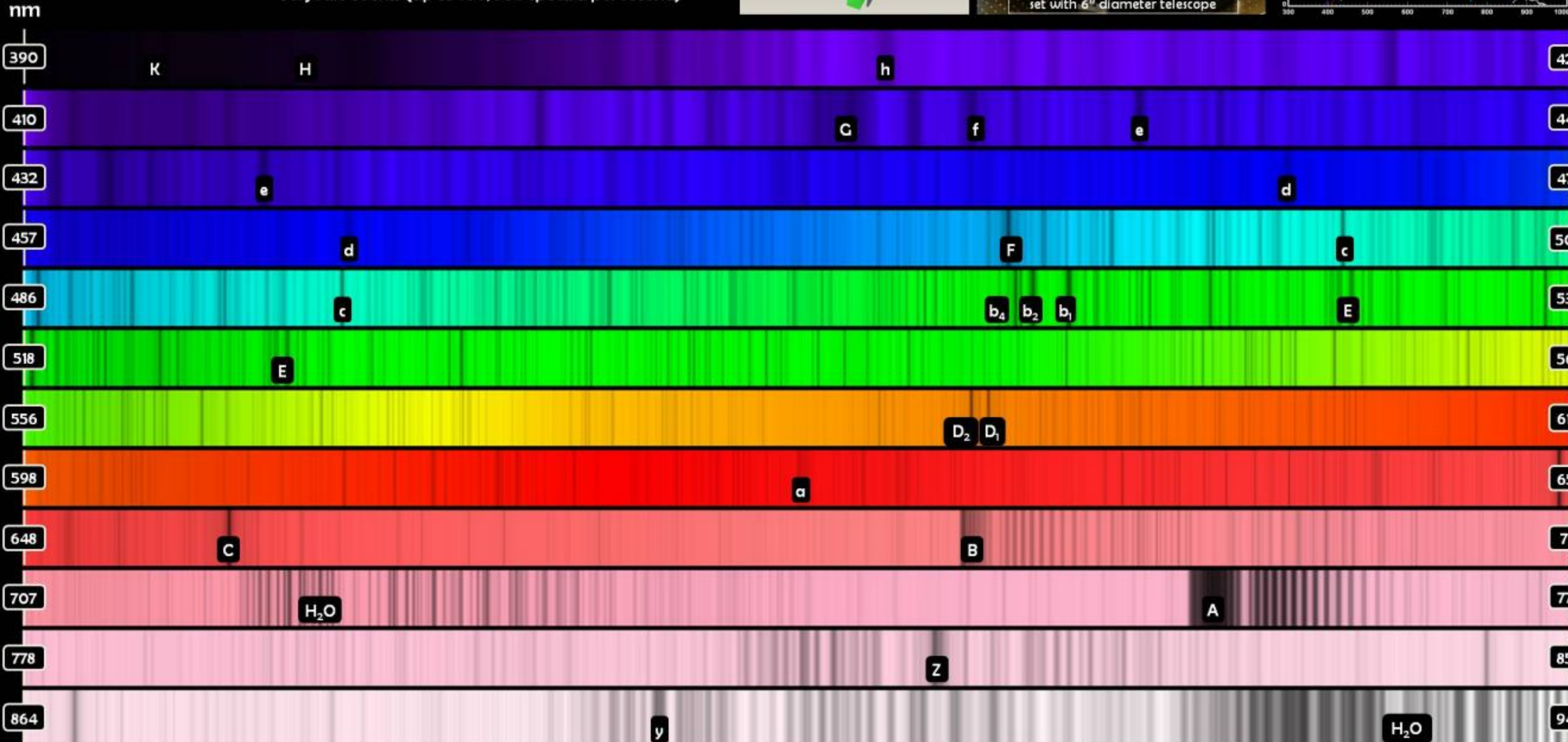
with the major Fraunhofer lines

High Speed Echelle Spectrometer developed for recording very fast events (up to 100,000 spectra per second)



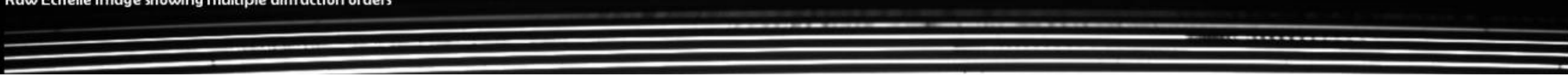




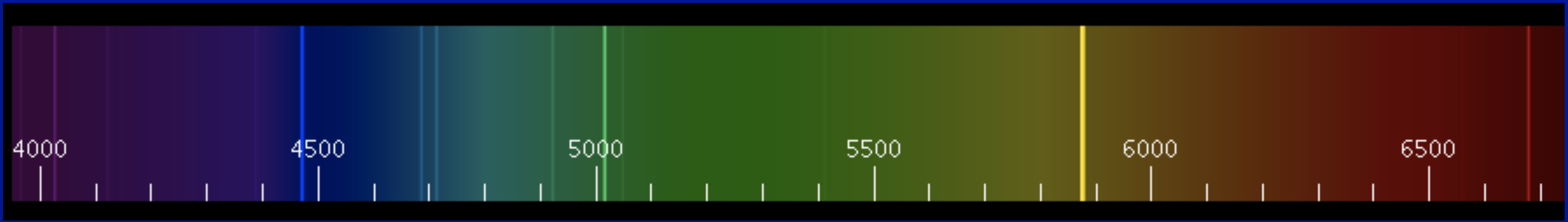


K	H	h	G		f	e	d	F	c	b_4		b_2	b_1	E	D_2	D_1	a	C	B		A	Z	y	
Ca+	Ca+	Hδ	Ca	Fe	H	Fe	Fe	Hβ	Fe	Mg	Fe	Mg	Mg	Fe	Na	Na	O_2	Hα	O_2	H_2O	O_2	O_2	O_2	H_2O
393.368	396.847	410.175	430.774	430.790	434.0	438.355	466.814	486.134	495.761	516.733	516.891	517.270	518.362	527.0	588.995	589.592	627.661	656.281	686.719	720.0	759.370	822.696	898.765	940.0

Raw Echelle image showing multiple diffraction orders

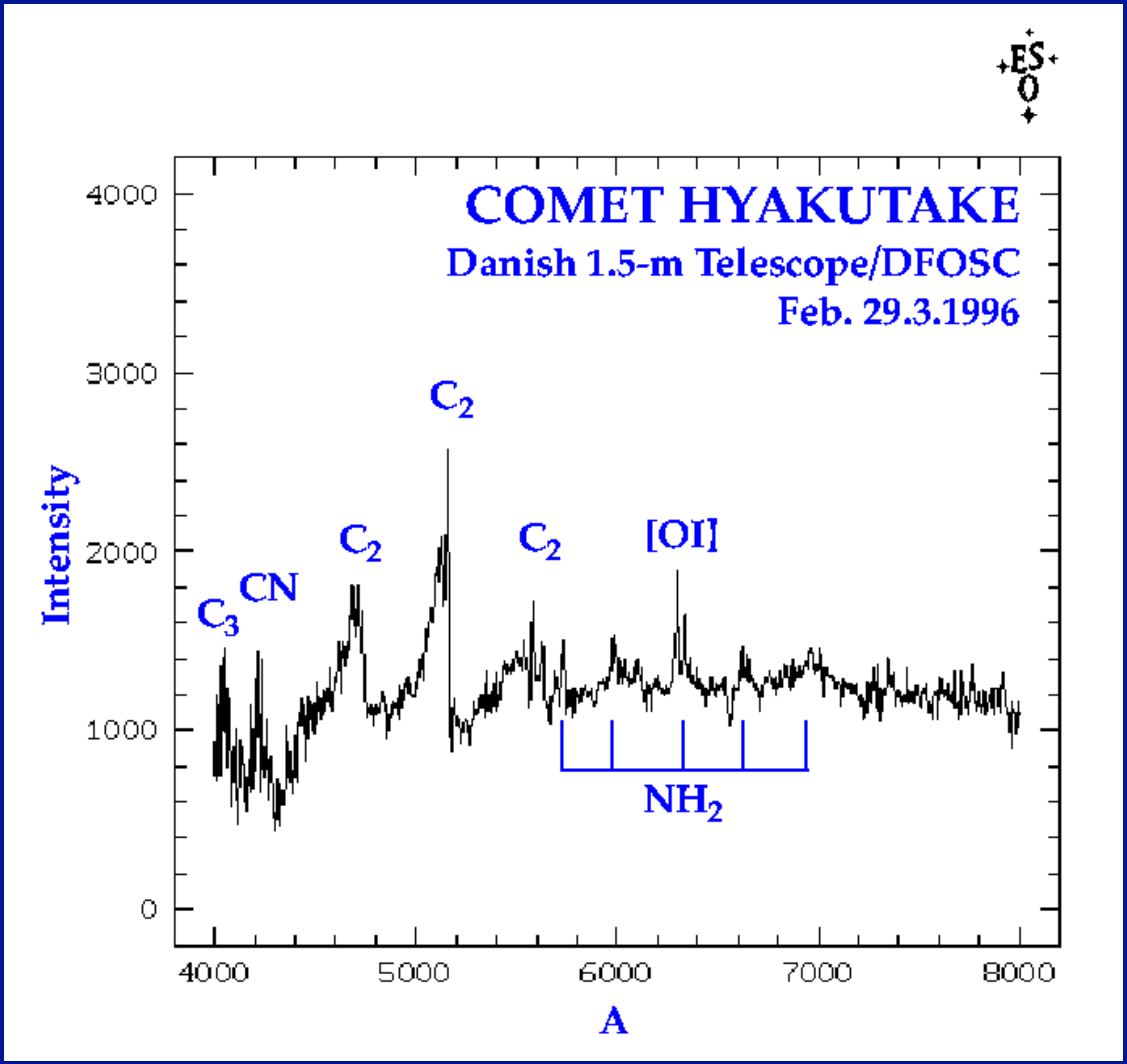


Spectrum of Helium (He) Gas



Discovered in 1868 by Pierre Jannsen during a solar eclipse
Subsequently seen and named by Norman Lockyer

Example: spectra - comet Hyakutake



HI absorption in 1946+708

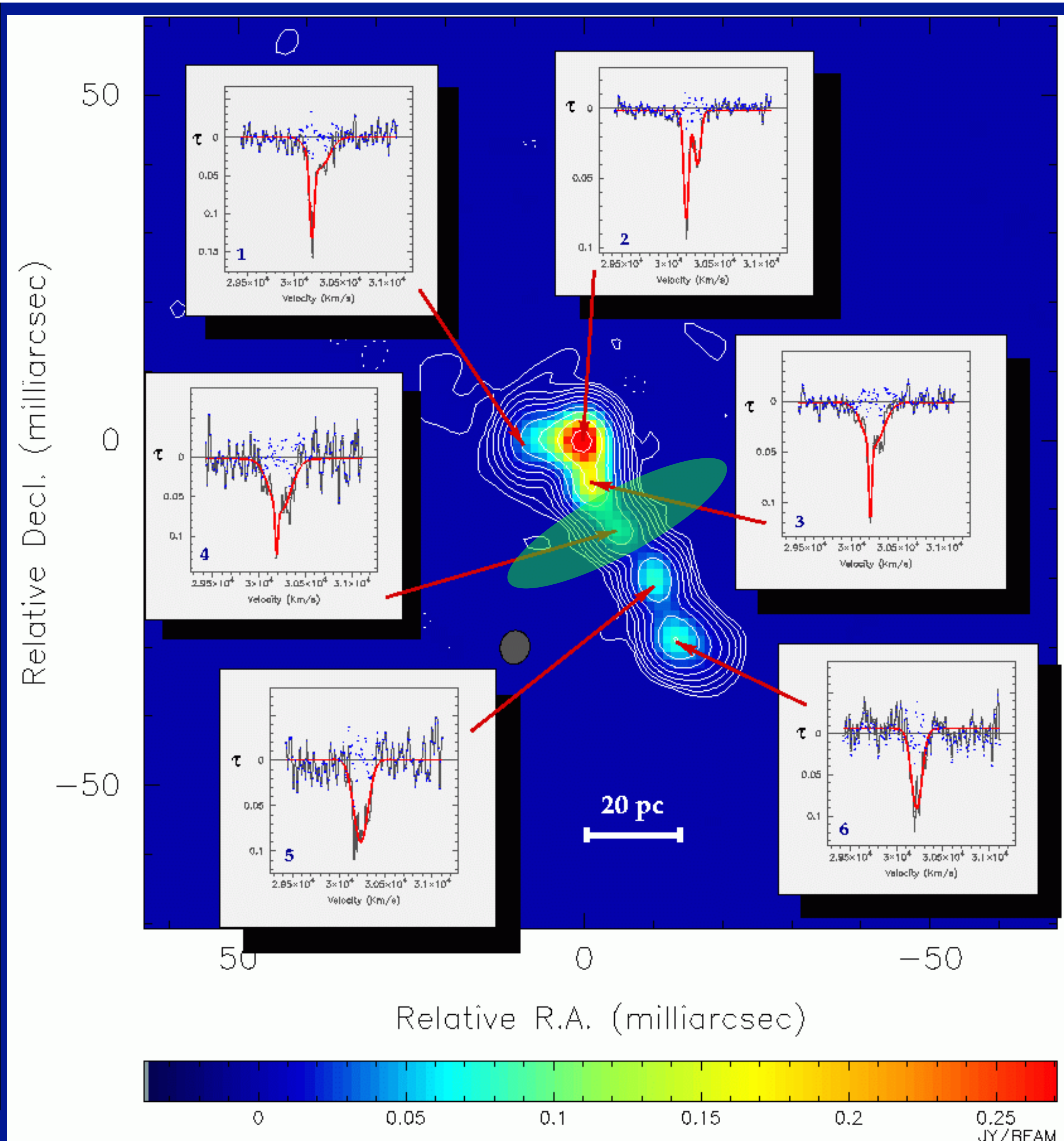
Peck & Taylor (2001)

“Global” VLBI observations

core:

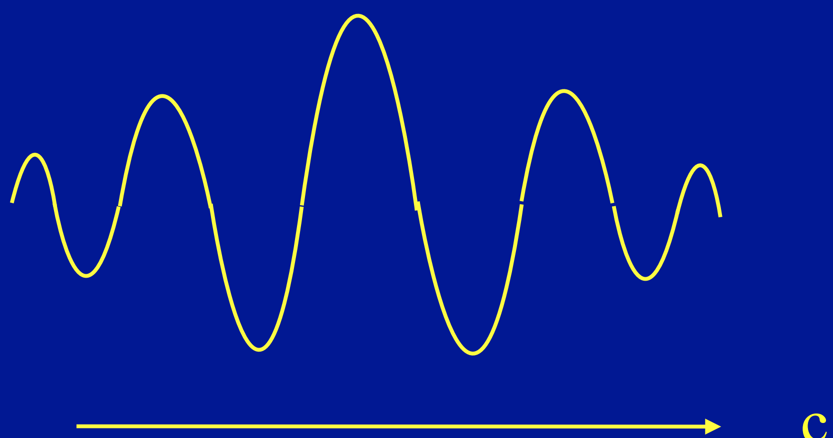
FWHM = 350 km/s

M ~ 10^8 M_{sun}



The Particle Nature of Light

On microscopic scales (scale of atoms), light travels as individual packets of energy, called photons.



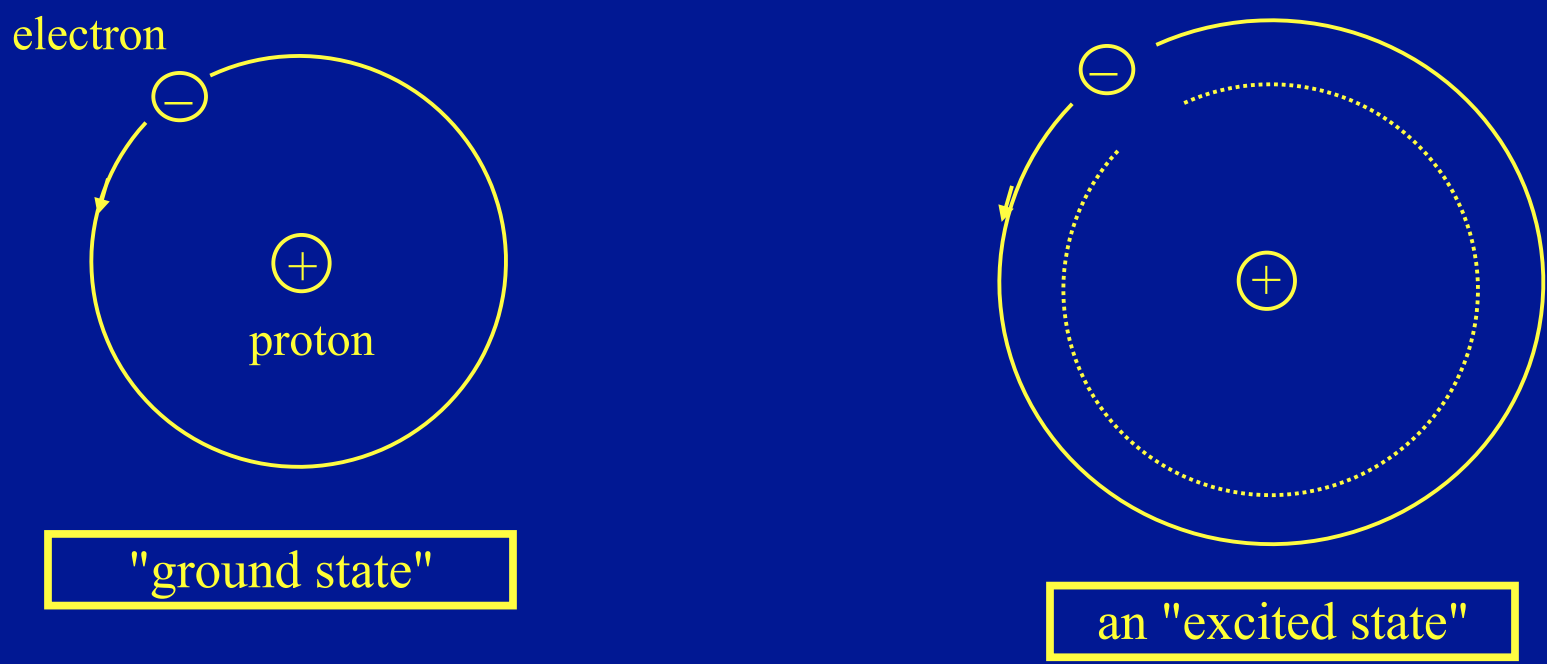
photon energy is proportional to radiation frequency:

$E \; \alpha \; \nu$ (or $E \; \alpha \; \frac{1}{\lambda}$)

example: ultraviolet photons are more harmful than visible photons.

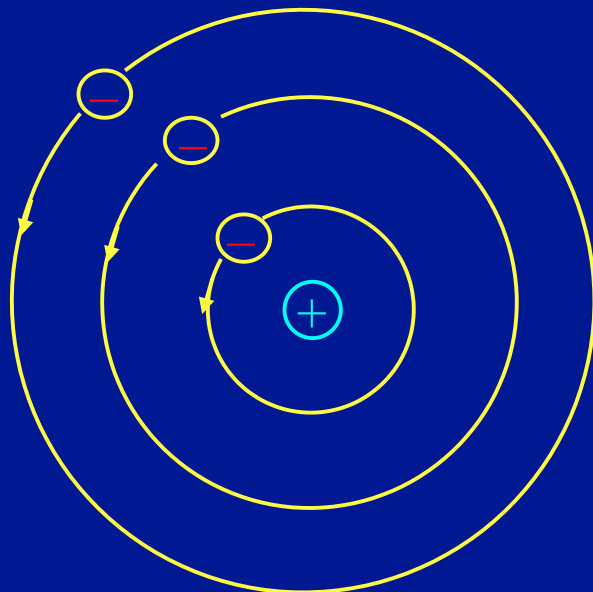
The Nature of Atoms

The Bohr model of the Hydrogen atom:



Ground state is the lowest energy state. Atom must gain energy to move to an excited state. It must absorb a photon or collide with another atom.

But, only certain energies (or orbits) are allowed:

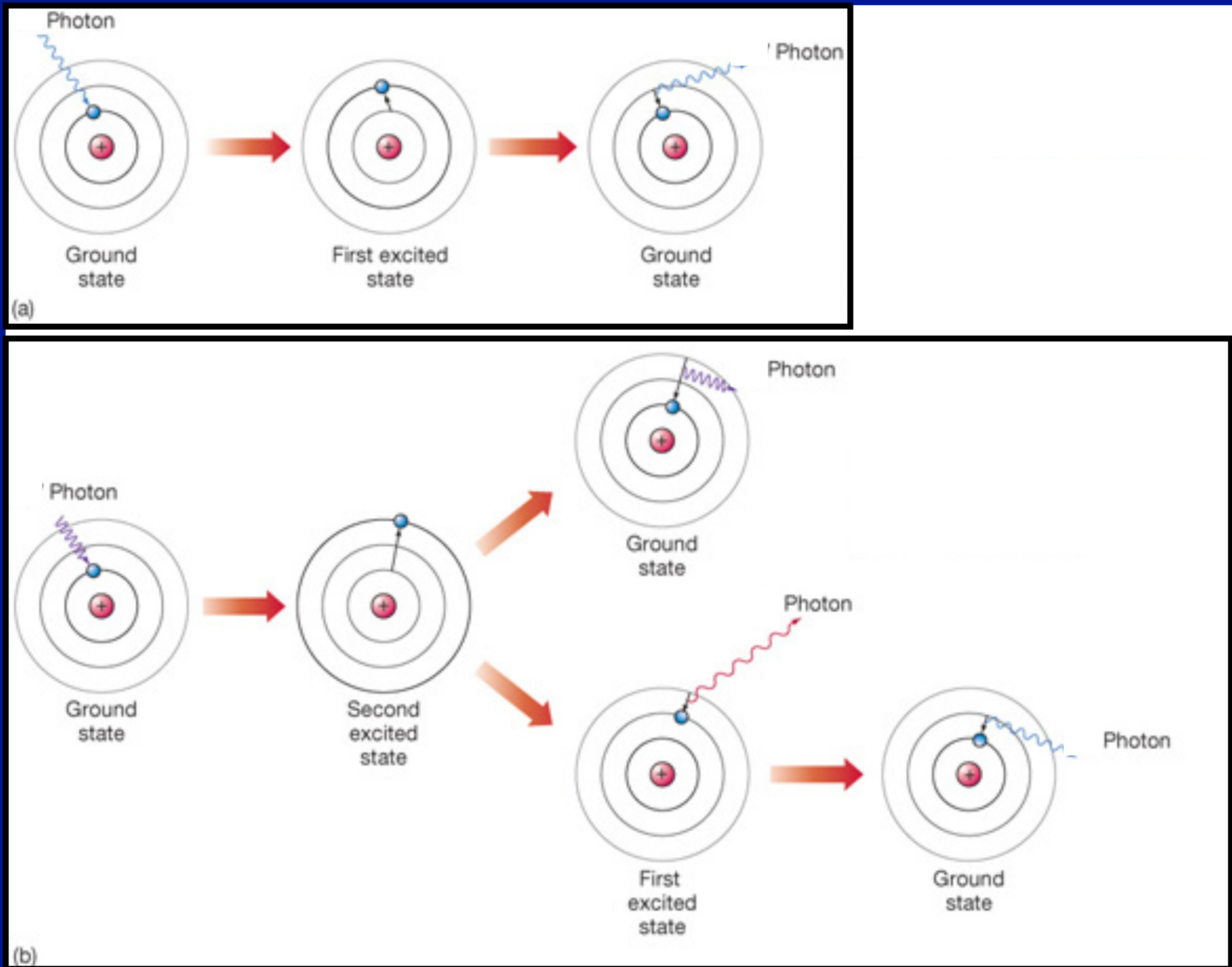


a few energy levels of H atom

The atom can only absorb photons with exactly the right energy to boost the electron to one of its higher levels.

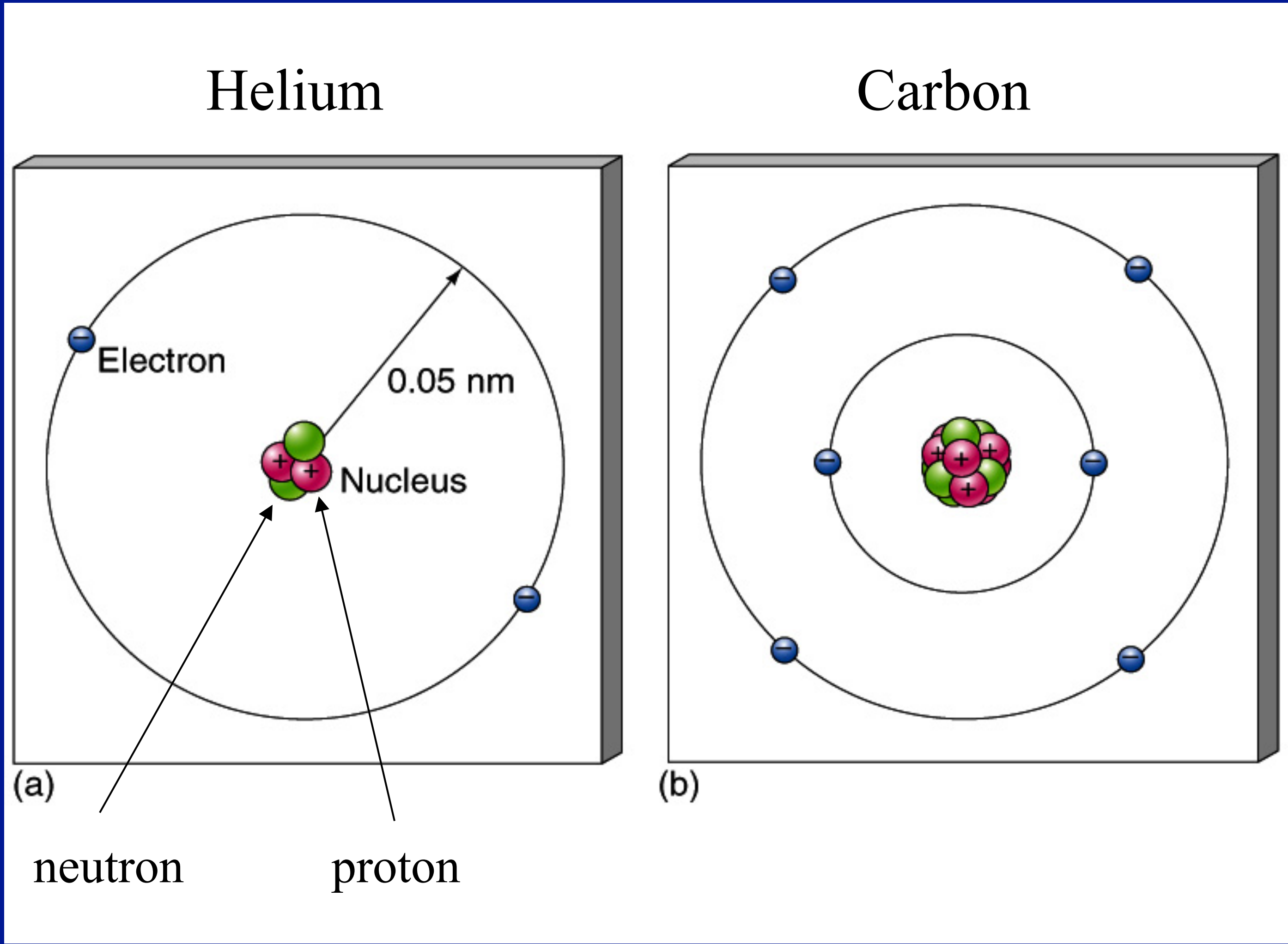
(photon energy α frequency)

When an atom absorbs a photon, it moves to a higher energy state briefly



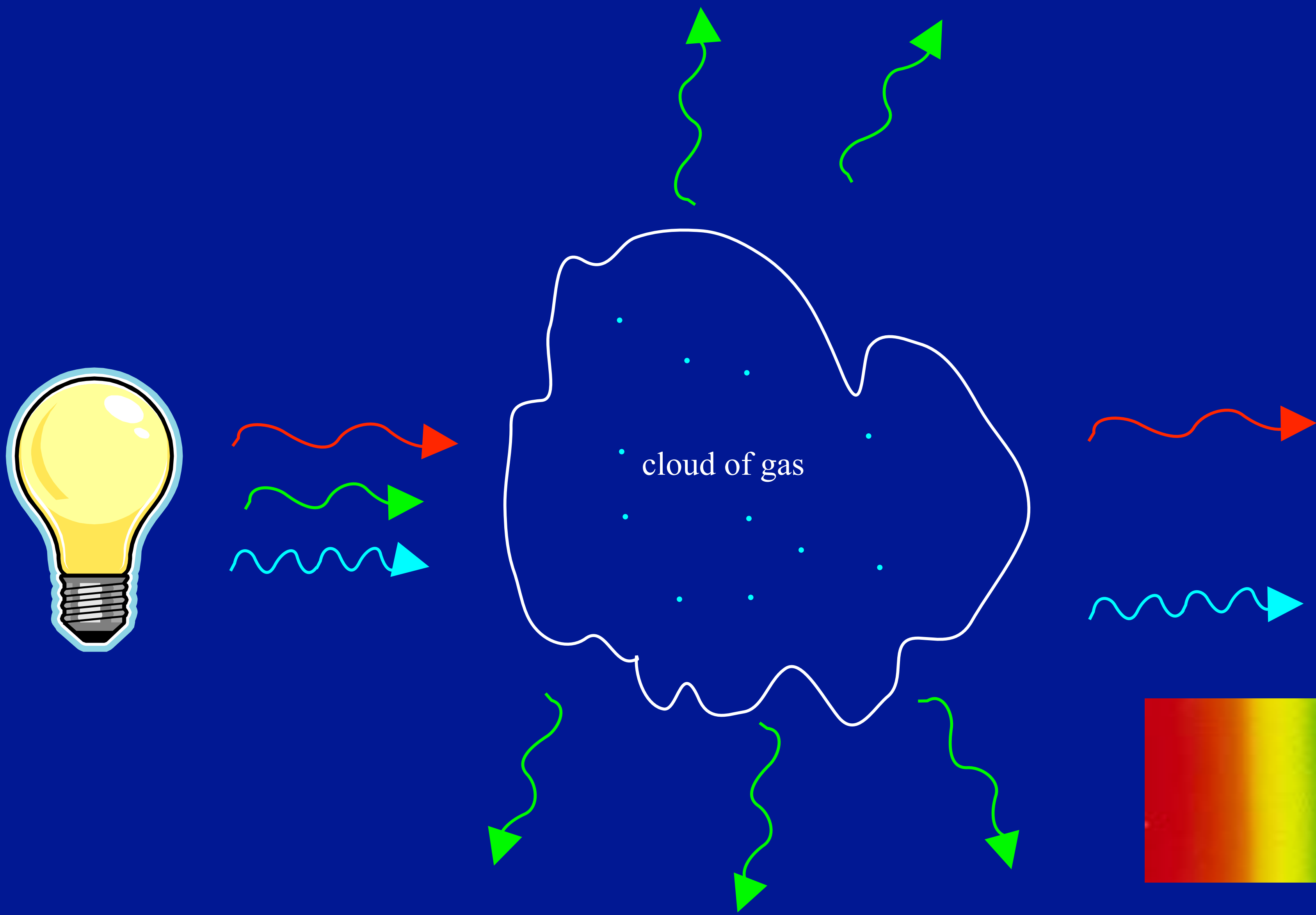
When it jumps back to lower energy state, it emits a photon - in a random direction

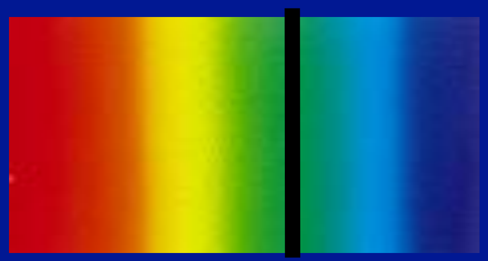
Other elements



Atoms have equal positive and negative charge. Each element has its own allowed energy levels and thus its own spectrum.

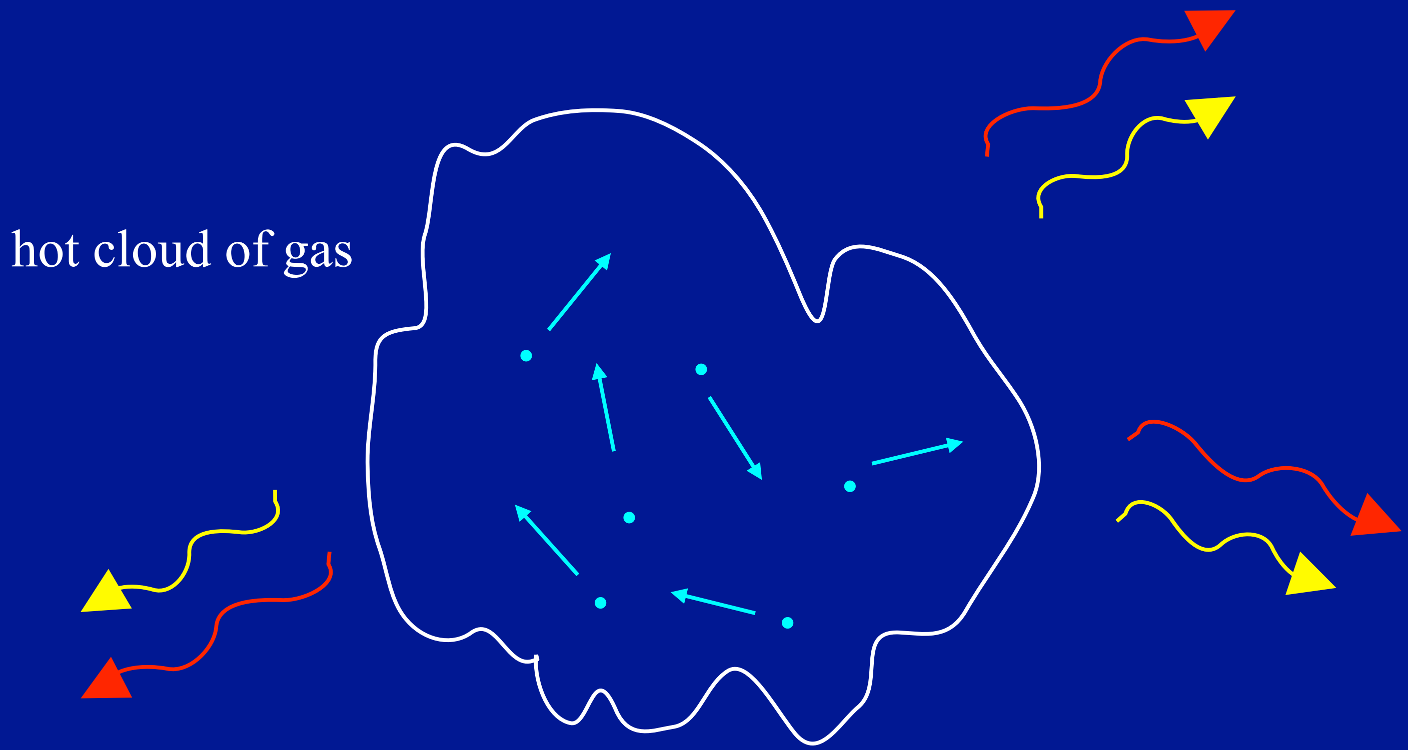
So why absorption lines?





The green photons (say) get absorbed by the atoms. They are emitted again in random directions. Photons of other wavelengths go through. Get dark absorption line at green part of spectrum.

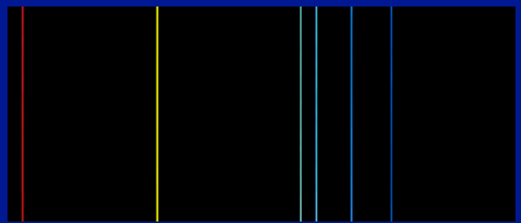
Why emission lines?



- Collisions excite atoms: an electron moves into a higher energy level

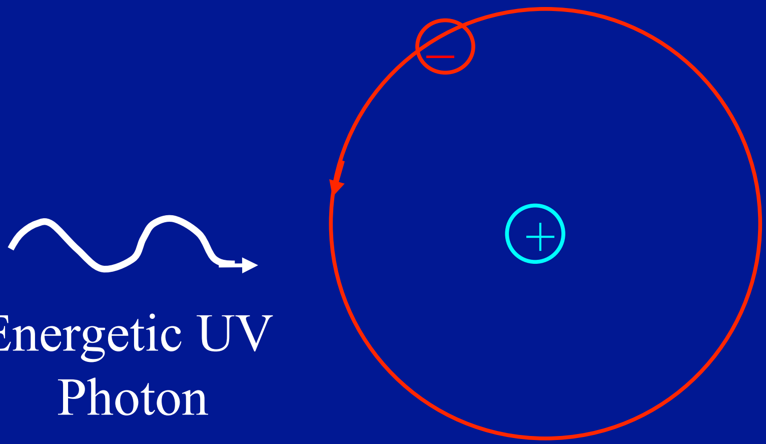
- Then electron drops back to lower level

- Photons at specific frequencies emitted.

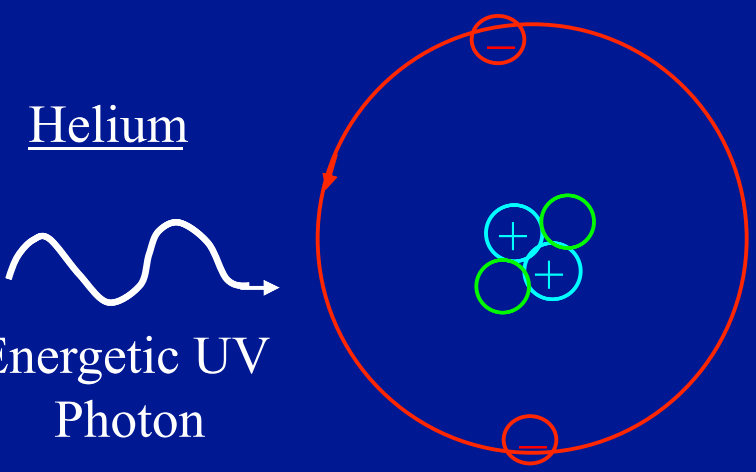


Ionization

Hydrogen



Helium



Two atoms colliding can also lead to ionization.

Clicker Question:

Astronomers analyze spectra from astrophysical objects to learn about:

A: Composition (what they are made of)

B: Temperature

C: line-of-sight velocity

D: Gas pressures

E: All of the above

Clicker Question:

Ionized Helium consists of two neutrons and:

A: two protons in the nucleus and 1 orbiting electron

B: two protons in the nucleus and 2 orbiting electrons

C: one proton in the nucleus and 1 orbiting electron

D: one proton in the nucleus and 2 orbiting electrons

E: two protons in the nucleus and 3 orbiting electrons

Clicker Question:

Why is the sky blue?

A: Molecules in the atmosphere scatter red light more than blue light.

B: Molecules in the atmosphere scatter blue light more than red light.

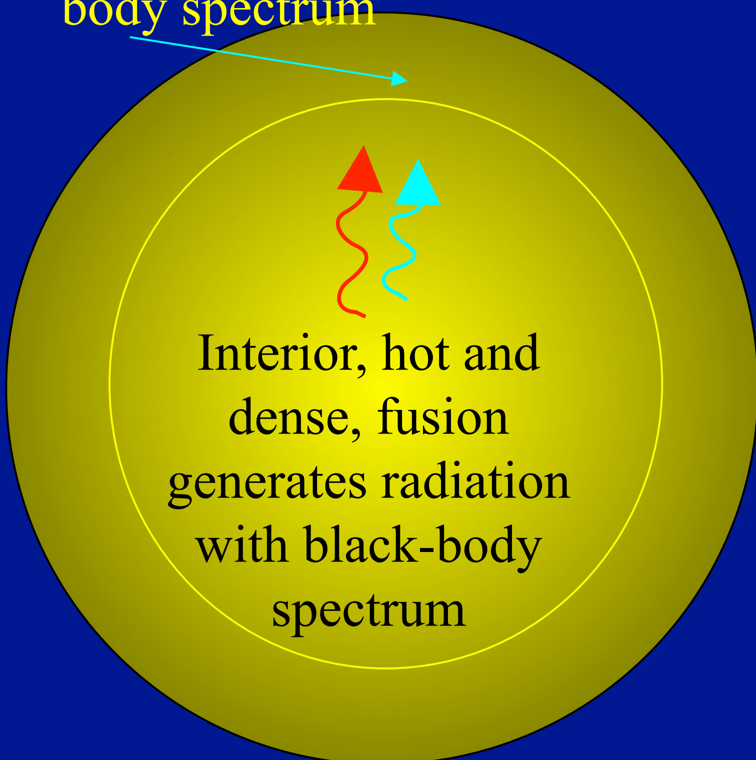
C: Molecules in the atmosphere absorb the red light

D: The sky reflects the color of the oceans.

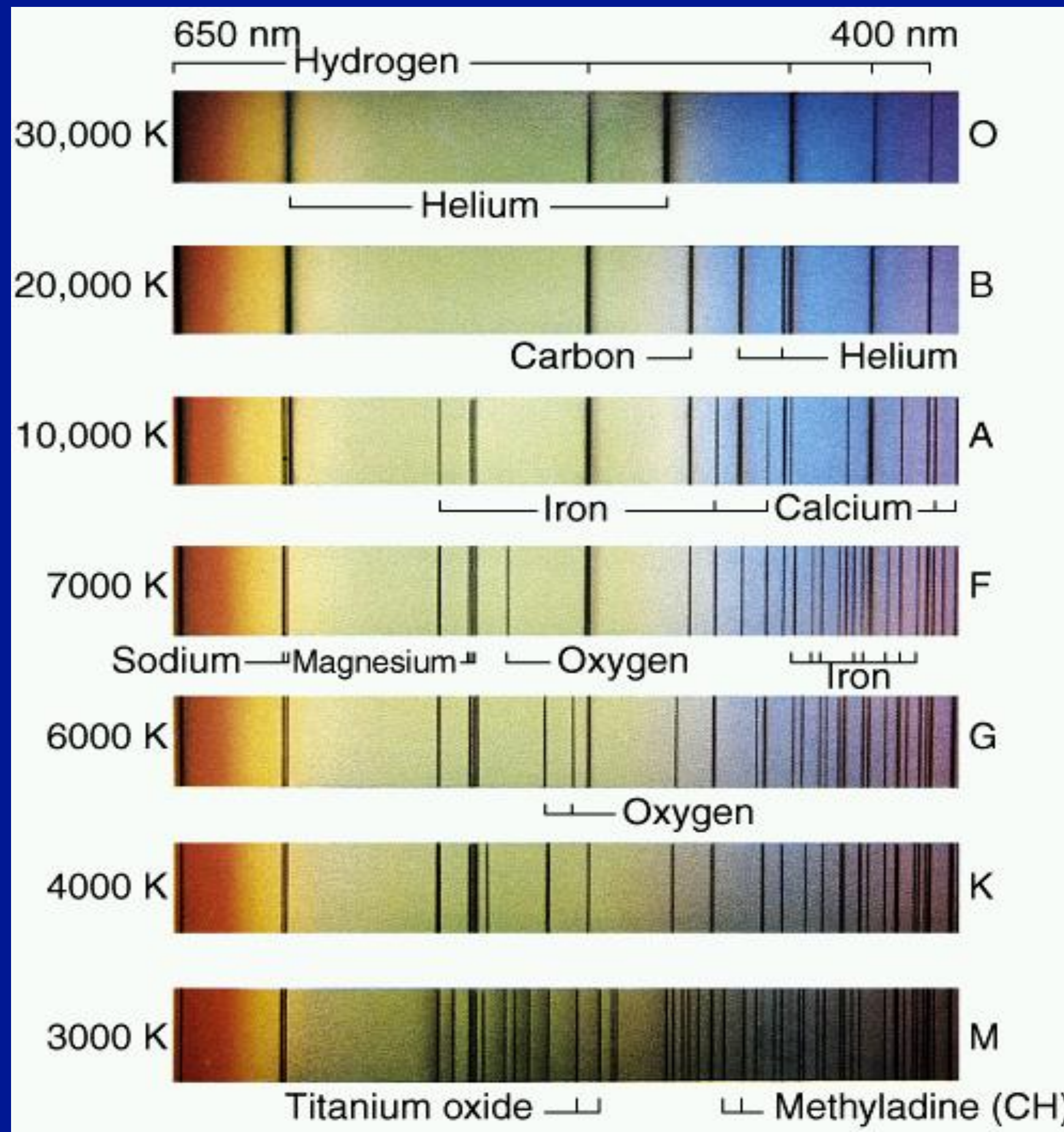
Stellar Spectra

Spectra of stars are different mainly due to temperature and composition differences.

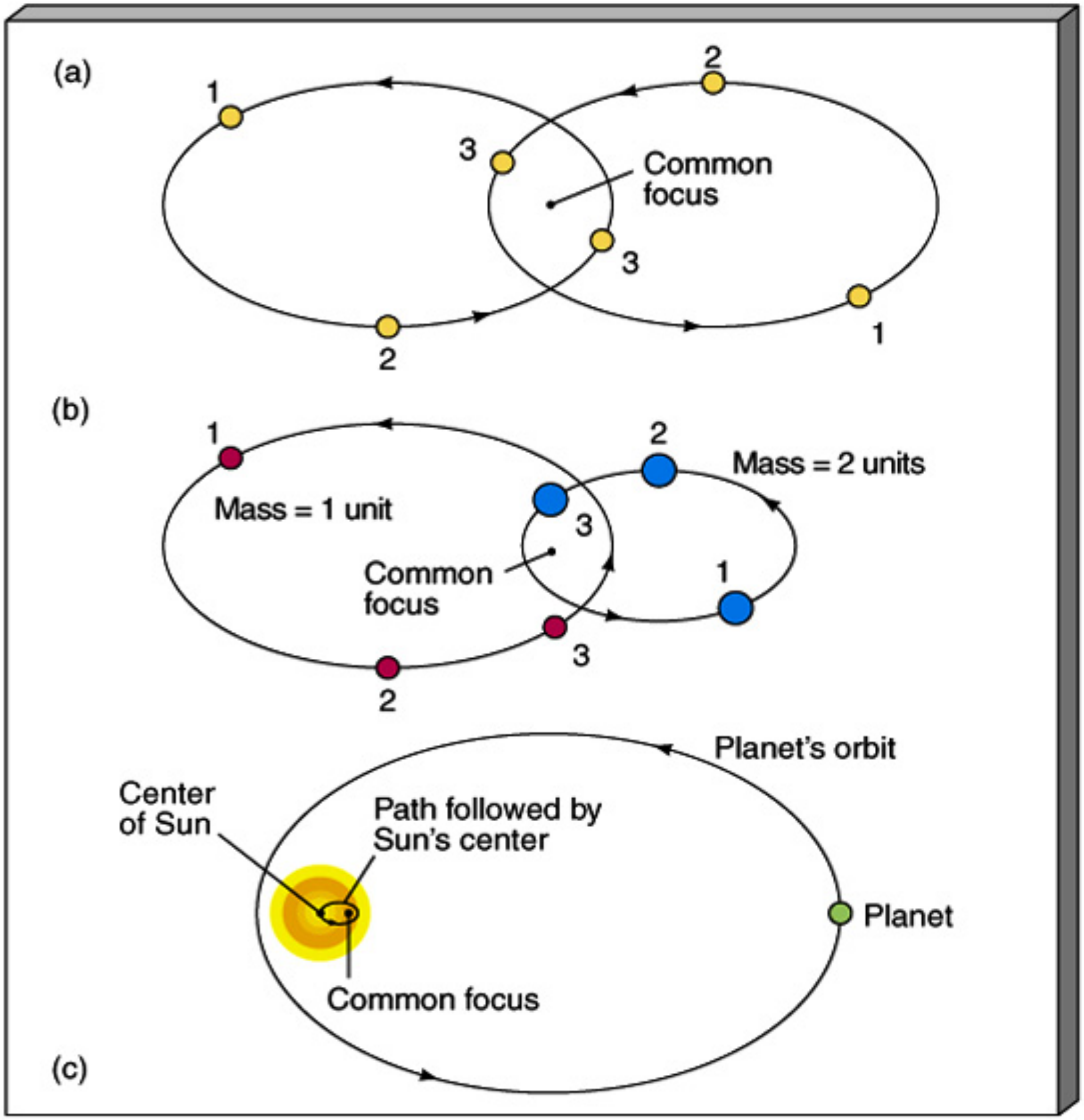
'Atmosphere', atoms and ions absorb specific wavelengths of the black-body spectrum



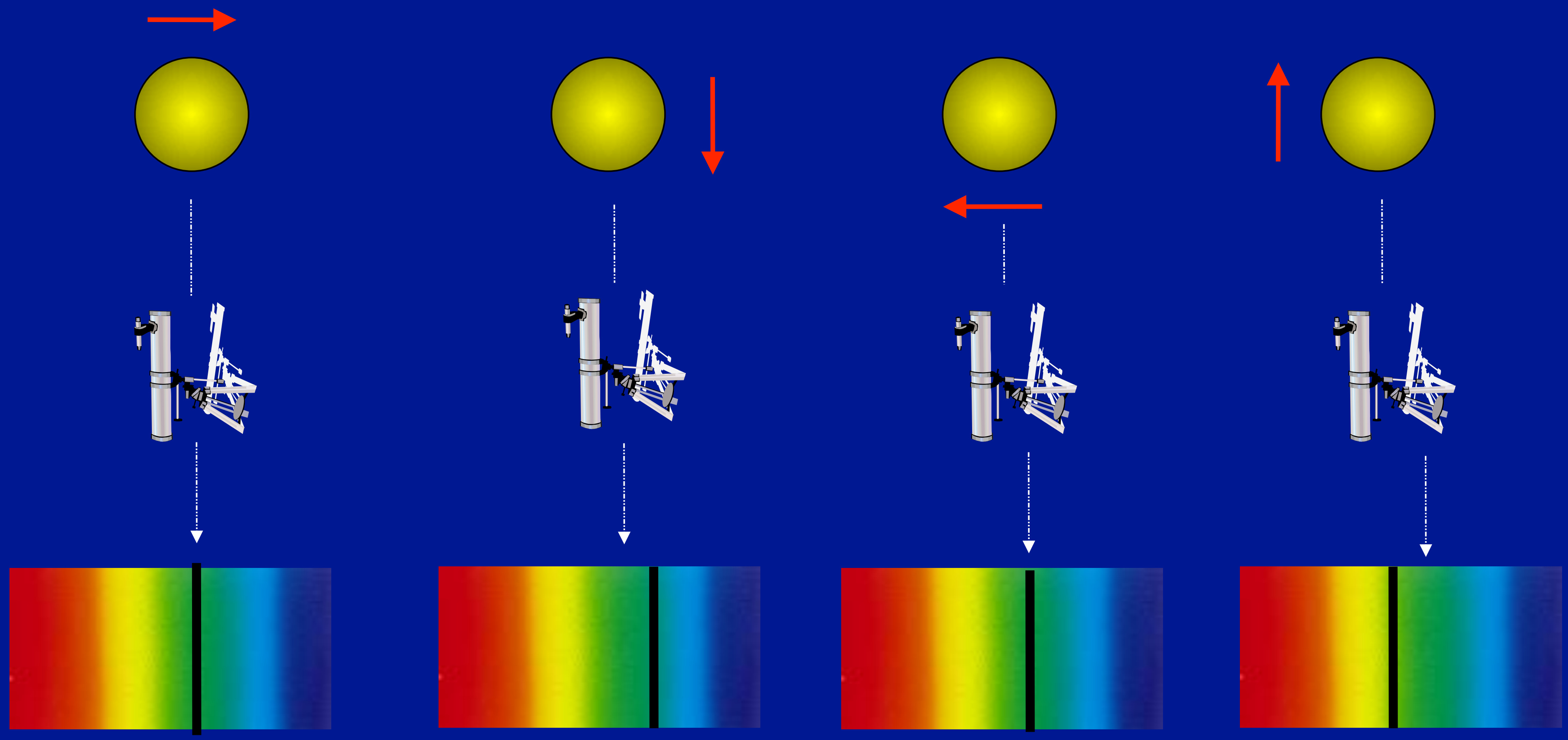
Star



We've used spectra to find planets around other stars.

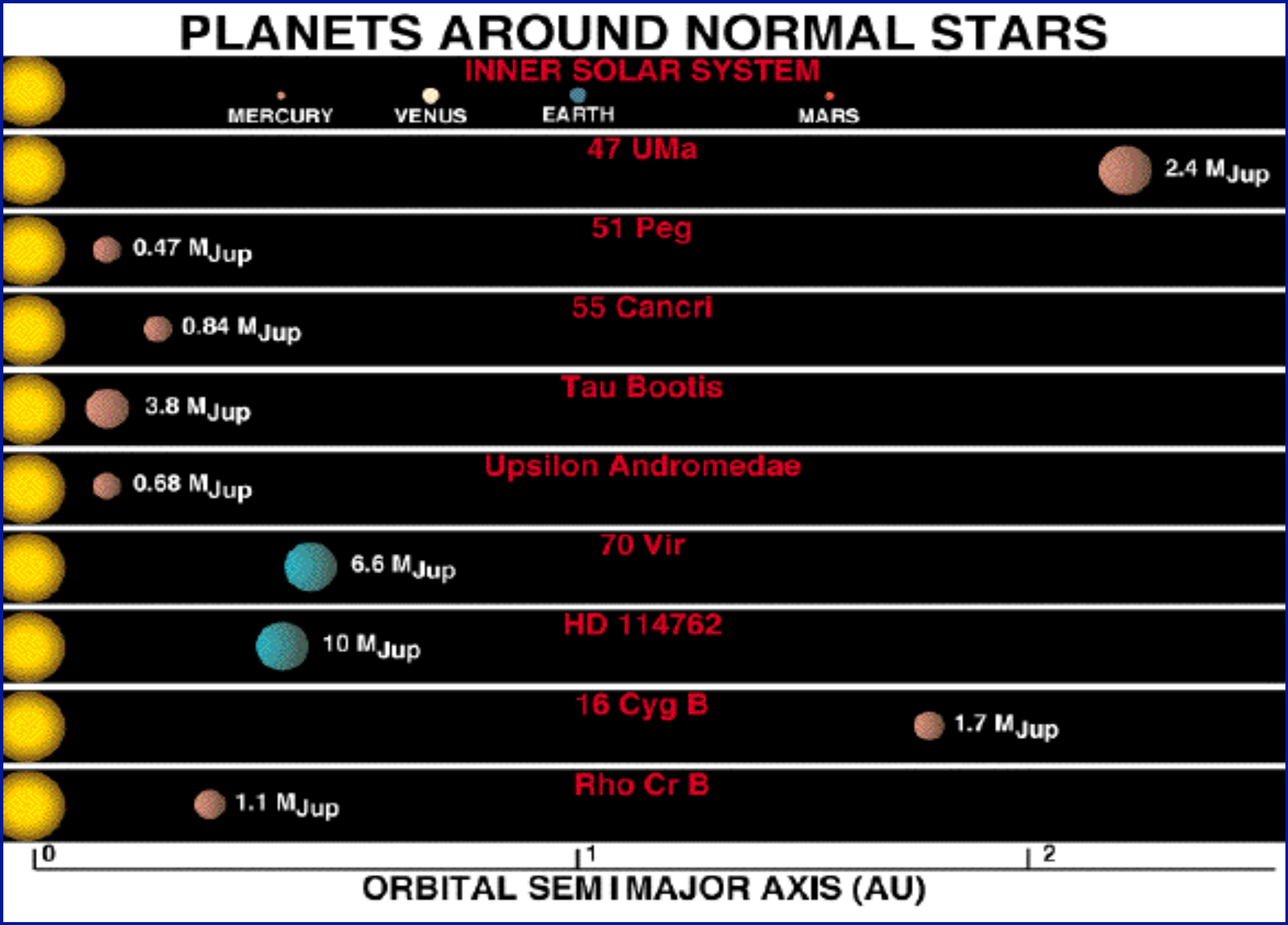


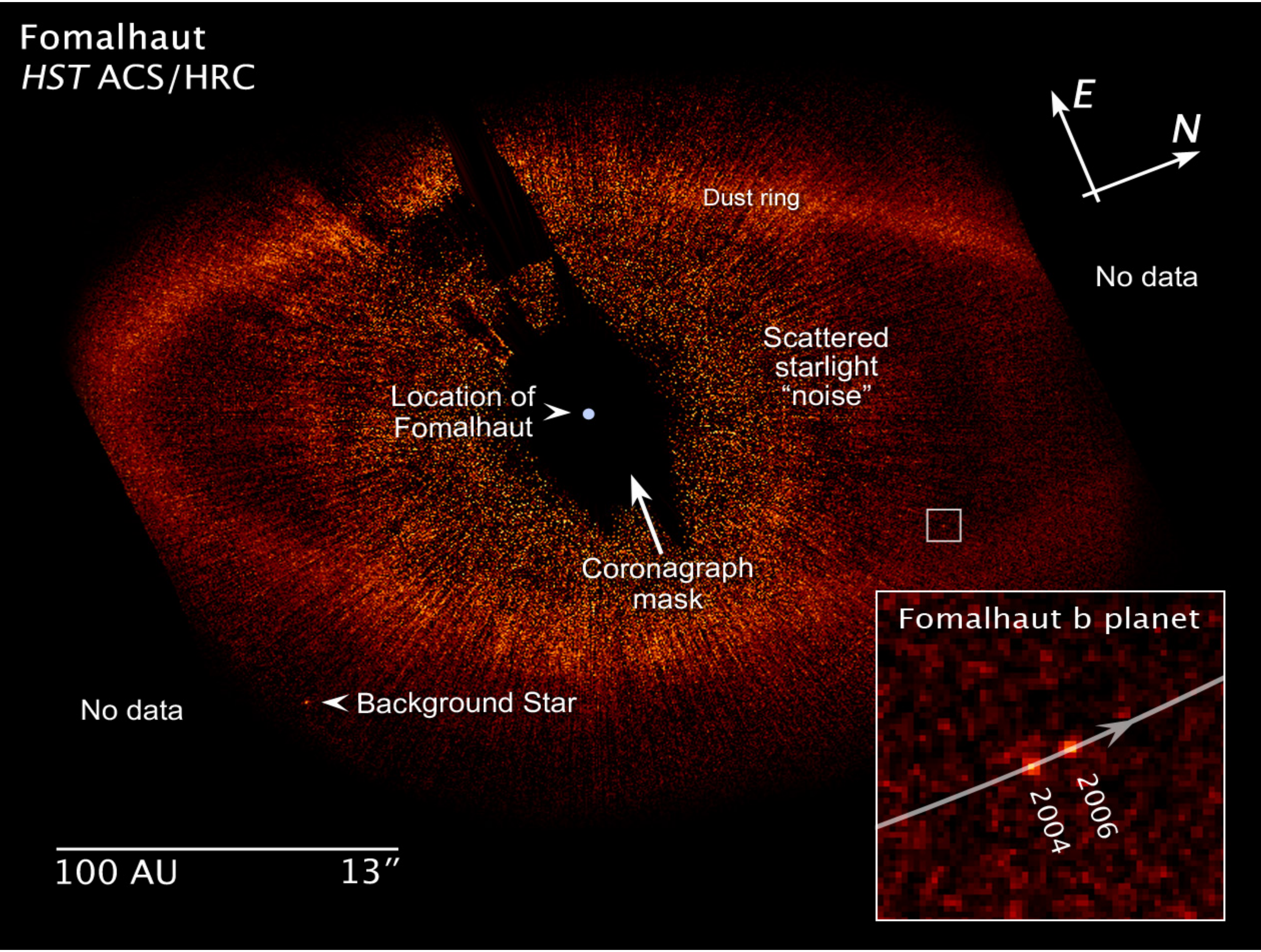
Star wobbling due to gravity of planet causes small Doppler shift of its absorption lines.



Amount of shift depends on velocity of wobble. Also know period of wobble. This is enough to constrain the mass and orbit of the planet.

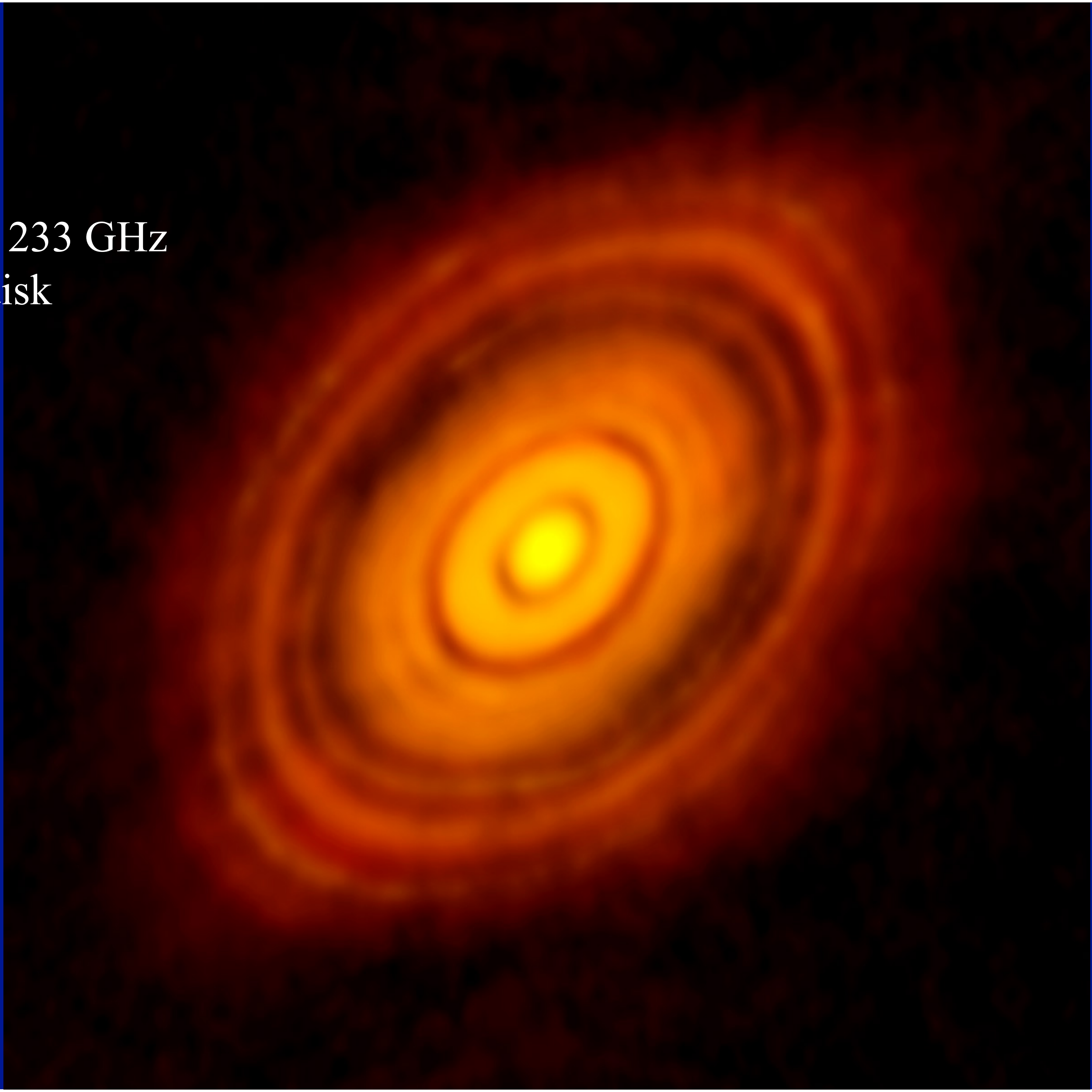
Over 2000 extrasolar planets known. Here are the first few discovered.




Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered starlight "noise"
Location of Fomalhaut
Coronagraph mask
Fomalhaut b planet
2004
2006
No data
Background Star
100 AU
13″

HL Tau

ALMA image at 233 GHz
235 AU across disk



Molecules

Two or more atoms joined together.

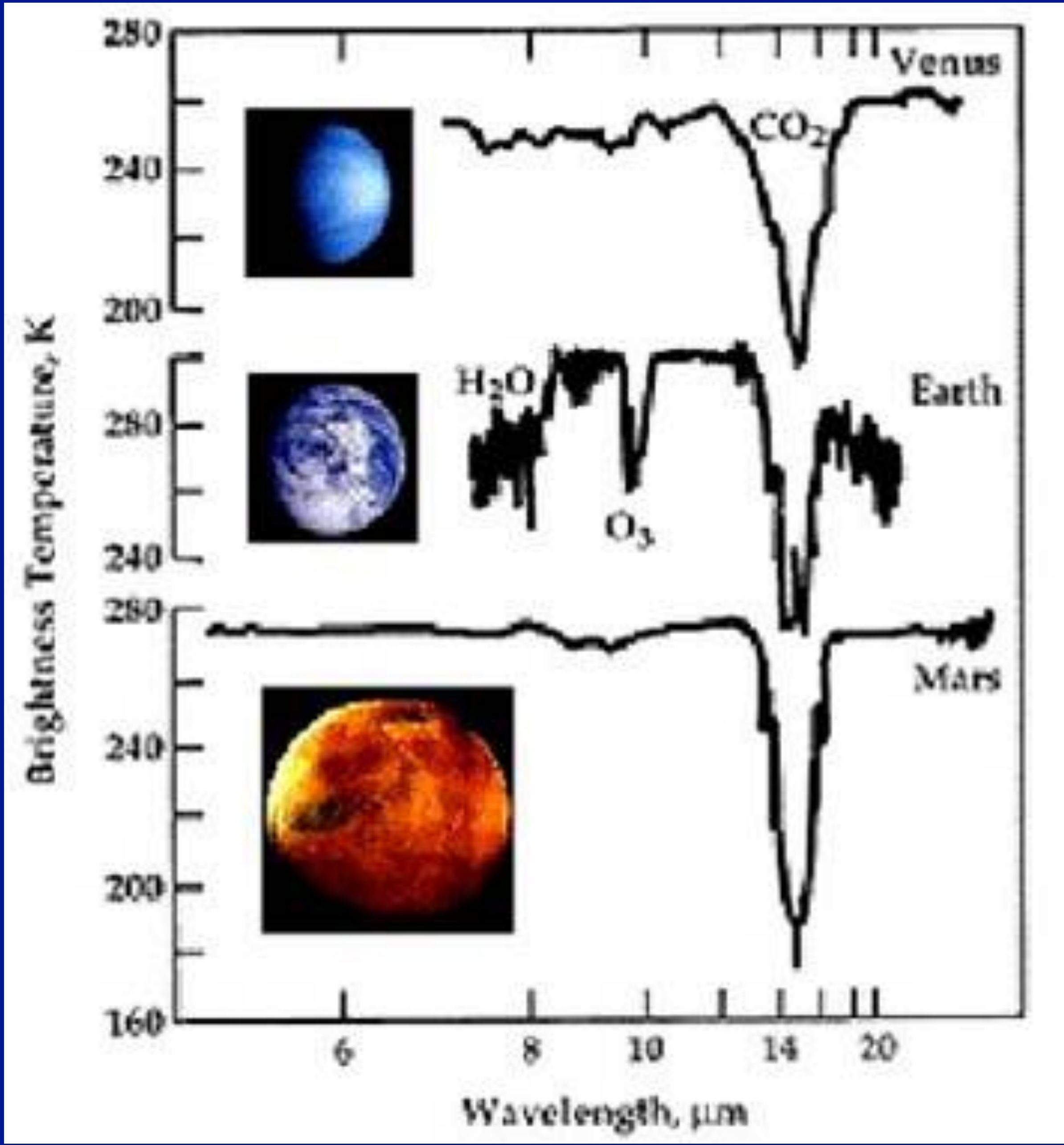
They occur in atmospheres of cooler stars,
cold clouds of gas, planets.

Examples

$H_2 = H + H$
$CO = C + O$
$CO_2 = C + O + O$
$NH_3 = N + H + H + H$ (ammonia)
$CH_4 = C + H + H + H + H$ (methane)

They have
- electron energy levels (like atoms)
- rotational energy levels
- vibrational energy levels

Searching for Habitable planets around other stars



Molecule vibration and rotation