



# Universidad Nacional de Río Negro

## Int Partículas, Astrofísica & Cosmología - 2021

- **Unidad**      02-Astrofísica, estrellas y planetas
- **Clase**        UO2 C01 - 5/16
- **Fecha**        01 Sep 2021
- **Cont**          Estrellas
- **Cátedra**      Asorey

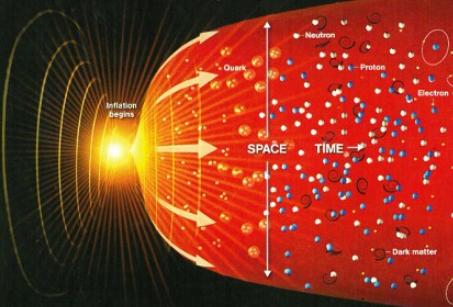


# Contenidos: un viaje en el tiempo y el espacio

HOW DID OUR UNIVERSE BEGIN?

**Infación**  
In less than a nanosecond a massive energy field inflates space and time so much that it's filled with a soup of subatomic particles called quarks.  
Age:  $10^{-3}$  milliseconds  
Size: Infinitesimal to golf ball

**Early building blocks**  
The universe expands, cools. Quarks clump into protons and neutrons, which then form nuclei. Electrons fill gaps between building blocks of atomic nuclei. Perhaps dark matter forms.  
Age:  $10^{-2}$  milliseconds  
Size: .01 millimeters



## COSMIC QUESTIONS

In the 20th century the universe became a story—a scientific one. It had always been seen as static and eternal. Then astronomers observed other galaxies flying away from ours, and Einstein's general relativity theory implied space itself was expanding—which meant the universe had once been denser. What had seemed eternal now had a beginning and an end. But what beginning? What end? Those questions are still open.

### WHAT IS OUR UNIVERSE MADE OF?

Stars, dust and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy, an unknown energy field or property of space that counters gravity, providing an explanation for observations that the expansion of space is accelerating.

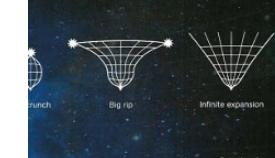


## Tres generaciones de la materia (fermiones)

	I	II	III	
masa→	$2.4 \text{ MeV}/c^2$	$1.27 \text{ GeV}/c^2$	$171.2 \text{ GeV}/c^2$	
carga→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	
espín→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
nombre→	u up	c charm	t top	
Quark	d down	s strange	b bottom	g Gluon
masa→	$4.8 \text{ MeV}/c^2$	$104 \text{ MeV}/c^2$	$4.2 \text{ GeV}/c^2$	$? \text{ GeV}/c^2$
carga→	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	$0$
espín→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$0$
nombre→	e Electrón	$\nu_e$ Neutrino electrónico	$\nu_\mu$ Neutrino muónico	$\nu_\tau$ Neutrino tauónico
Lepton	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1,777 \text{ GeV}/c^2$	$80.4 \text{ GeV}/c^2$
	$-1$	$-1$	$-1$	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$1$
	e Electrón	$\mu$ Muón	$\tau$ Tau	$W^\pm$ Boson W
Bosones de gauge				

### HOW WILL IT END?

Will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the presence of dark energy, a kind of antigravity. Perhaps the acceleration of expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand endlessly for billions of years, long after all stars have died.



## Unidad 1 Partículas, el más pequeño



By through the universe on our digital edition  
LONDON PHOTOS: ANDREW TAYLOR; GENEVA: PHILIPPE DESMAZES/GETTY IMAGES; ART: MONTAGNA DESIGN; SOURCES: CHARLES BENNETT, JOHN HESTER, ANDREW LISTER, ANDREW LISTER, UNIVERSITY OF CHICAGO; COURTESY OF CERN; NATIONAL GEOGRAPHIC SOCIETY

# Contenidos: un viaje en el tiempo y el espacio

## HOW DID OUR UNIVERSE BEGIN?

Some 13.8 billion years ago our entire visible universe was contained in an unimaginably hot, dense point, a billionth the size of a nuclear particle. Since then it has expanded—a lot—fighting gravity all the way.

**Inflation**  
In less than a nanosecond a massive energy field inflates space 10<sup>26</sup> times, stretching it with a soup of subatomic particles called quarks.

**Age:** 10<sup>-2</sup> milliseconds  
**Size:** Infinitesimal to golf ball

**Early building blocks**  
The universe expands, cools. Quarks clump into protons and neutrons; then strings of atoms begin to form. Perhaps dark matter forms.

**Age:** .01 milliseconds  
**Size:** 0.1-millionth present size

**First nuclei**  
As the universe continues to cool, the lightest nuclei of hydrogen will form, then helium, then other elements as the temperature drops.

**Age:** .01 seconds  
**Size:** Present size

**First atoms, first light**  
As electrons begin orbiting nuclei, creating atoms, the glow from their orbital motion is unveiled. This light is as far back as our instruments can see.

**Age:** .01 to 200 seconds  
**Size:** .0009 present size

**The “dark ages”**  
For 300 million years this cosmic fog of neutral hydrogen is the only light. Clumps of matter that will become galaxies glow brightest.

**Age:** 380,000 to 300 million years  
**Size:** .0009 to 0.1 present size

**Gravity wins: first stars**  
Dense gas clouds collapse under their own gravity and of dark matter to eventually form galaxies and stars. Nuclei fusion lights up the stars.

**Age:** 300 million years  
**Size:** 0.1 present size

**Antigravity wins**  
After being slowed for billions of years, dark energy speeds up again. The culprit: dark energy. Its nature: unclear.

**Age:** 10 billion years  
**Size:** .77 present size

**Today**  
The universe continues to expand, becoming ever less dense. As a result, fewer new stars and galaxies are forming.

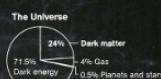
**Age:** 13.8 billion years  
**Size:** Present size

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## WHAT IS OUR UNIVERSE MADE OF?

Stars, dust and gas—the stuff we can discern—make up less than 5 percent of the universe. Their gravity can't account for how galaxies hold together. Scientists figure about 24 percent of the universe is a mysterious dark matter—perhaps exotic particles formed right after inflation. The rest is dark energy, an unknown energy field or property of space that counters gravity, providing an explanation for observations that the expansion of space is accelerating.



## WHAT IS THE SHAPE OF OUR UNIVERSE?

Einstein discovered that a star's gravity curves space around it. But is the whole universe curved? Might space close up on itself like a sphere or curve the other way, opening out like a saddle? By studying cosmic background radiation, scientists have found that the universe is poised between the two: just dense enough with just enough gravity to be almost perfectly flat, at least the part we can see. What lies beyond we can't know.



## Unidad 2 Astrofísica, escalas medias

### DO WE LIVE IN A MULTIVERSE?

What came before the big bang? Maybe other big bangs. The uncertainty principle holds that even the vacuum of space has density fluctuations. Inflation theory says our universe exploded from such a fluctuation—a random event that, odds are, had happened many times before. Our cosmos may be one in a sea of others just like ours—or nothing like ours. These other cosmos will very likely remain forever inaccessible to observation, their possibilities limited only by our imagination.

## HOW WILL IT END?

Which will win in the end, gravity or antigravity? Is the density of matter enough for gravity to halt or even reverse cosmic expansion, leading to a big crunch? It seems unlikely—especially given the power of dark energy, a kind of antigravity. Perhaps the acceleration in expansion caused by dark energy will trigger a big rip that shreds everything, from galaxies to atoms. If not, the universe may expand for hundreds of billions of years, long after all stars have died.



## Unidad 1 Partículas, lo más pequeño



By through the universe on  
our digital edition

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# U2: Astrofísica, escalas intermedias

## 5 encuentros, del 01/Sep al 29/Sep

- **Estrellas.**
  - Modelos politrópico. La fusión nuclear estelar.
  - Clasificación estelar. Diagrama H-R.
  - Evolución estelar. Nebulosas.
- **Planetas**
  - El Sistema Solar
  - Exoplanetas
  - Vida en el Universo: Astrobiología.
- **Trabajo unidad → fecha máxima de entrega 12/Nov**



# Estrellas





# Estrellas



Objeto astronómico que consiste en un esferoide de plasma autogravitante y luminoso

# Orión, el cazador



**Miremos al cielo... en el Norte!**



**Miremos al cielo... en el Ecuador!**



**Miremos al cielo... en el Sur!**

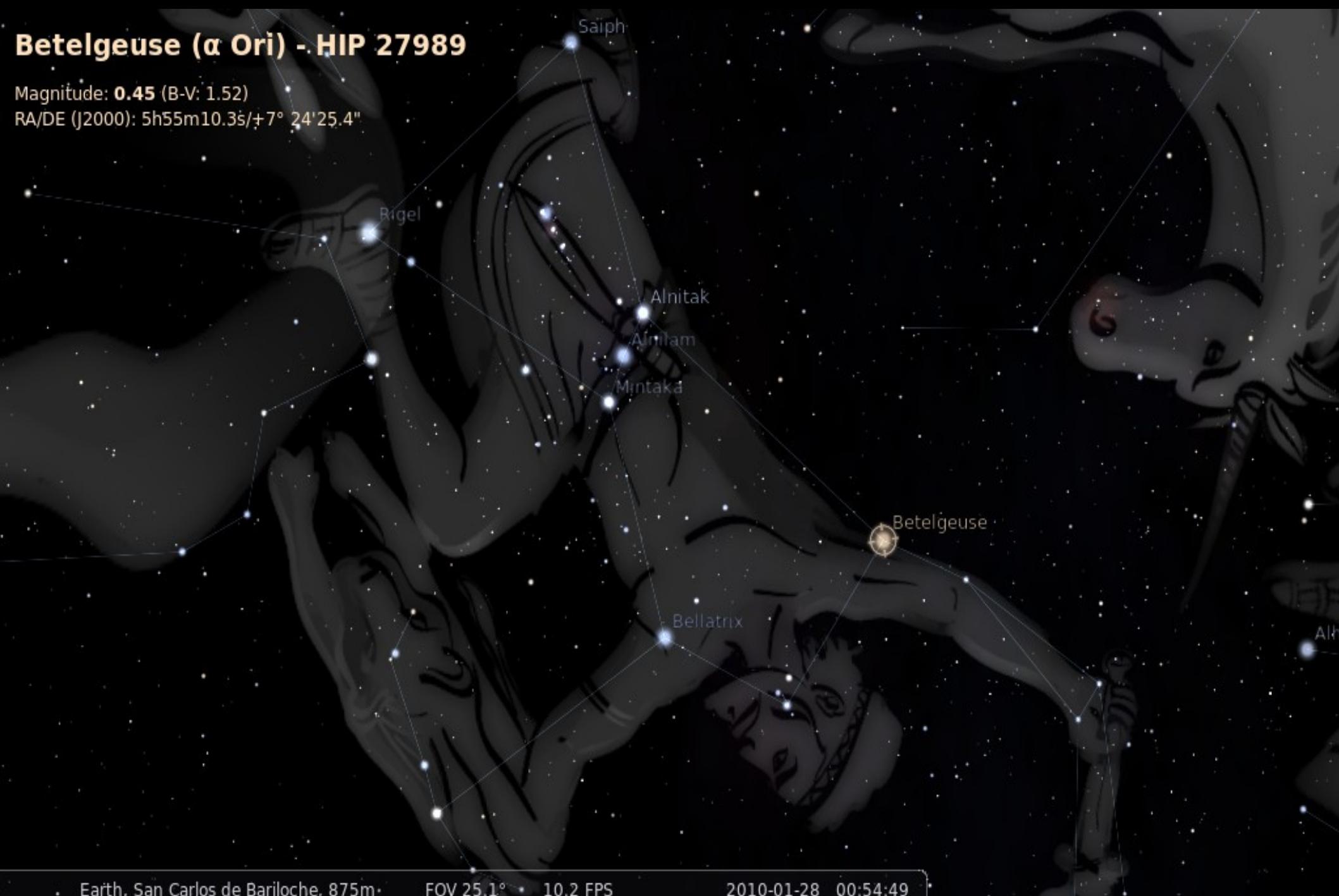


# Miremos al cielo... en el Sur!

## Betelgeuse ( $\alpha$ Ori) - HIP 27989

Magnitude: **0.45** (B-V: 1.52)

RA/DE (J2000): 5h55m10.3s /  $+7^{\circ} 24' 25.4''$



# Miremos al cielo... en el Sur!

Betelgeuse ( $\alpha$  Ori) - HIP 25125

Magnitude: **0.45** (B-V: 1.52)

RA/DE (J2000): 5h55m

**Betelgeuse ( $\alpha$  Ori) - HIP 25189**

Magnitude: **0.45** (B-V: 1.52)

RA/DE (J2000): 5h55m47.0s

**Rigel**

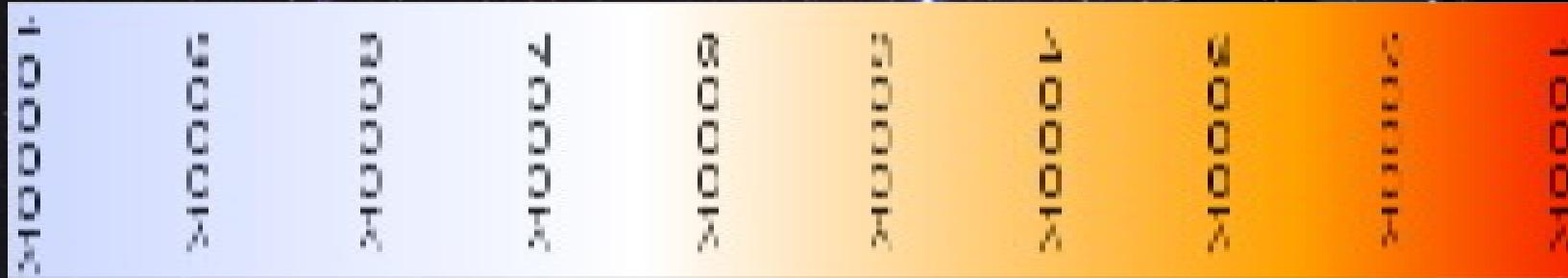
**Saiph**

**Nebulosa de Orion**

**Alnitak  
Alnilam  
Mintaka**

**Betelgeuse**

**Bellatrix**





# No todas son iguales

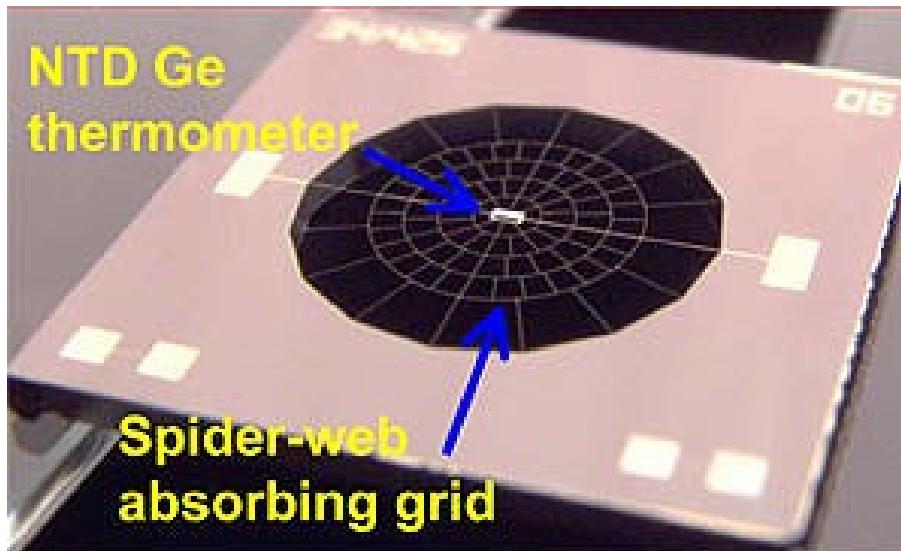
- Estado de evolución (edad)
- Temperatura
- Constitución inicial
- Masa
- **Energía emitida por unidad de tiempo: Luminosidad**
- Y además...

$$L = \frac{\Delta E}{\Delta t}$$

**No todas están a la misma distancia**

# ¿Cómo se mide la luminosidad?

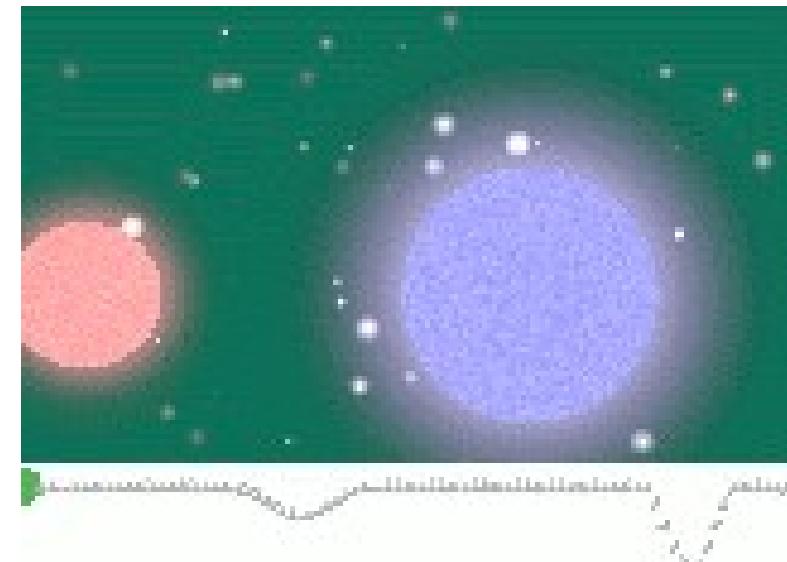
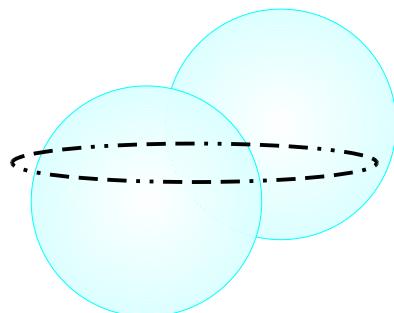
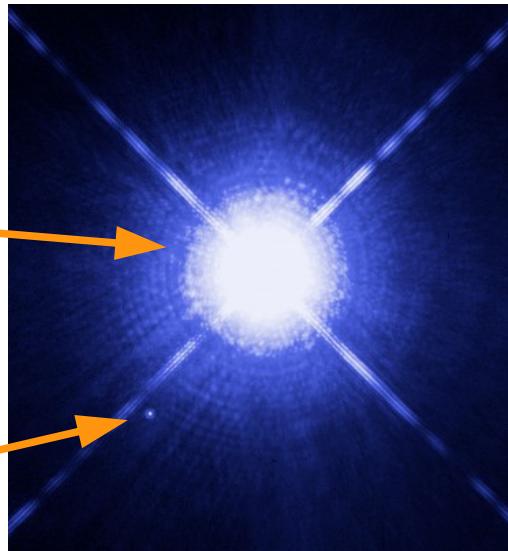
- **Bolómetro: instrumento para medir el flujo de radiación electromagnética en distintas bandas (IR,V,UV...)**
- Uso la definición del flujo sobre la superficie esfera:  $F = \frac{L}{4\pi d^2}$
- Conociendo la distancia  $d$ , puedo calcular la luminosidad:  $L = 4\pi d^2 F$   
Ó, conociendo  $L$ , calculo  $d$



$$d = \sqrt{\frac{L}{4\pi F}}$$

# Dos sistemas binarios

- Sistema Sirio ( $\alpha$ -CMa), 8.6 al
- Binaria (50.1a):  
Sirio A (A1), Sirio B(dA2)  
 $M=2 M_{\odot}$   $T=9900K$   
 $L=25 L_{\odot}$   $R=1.7R_{\odot}$
- Sistema Mintaka ( $\delta$ -Ori), 900 al
- Binaria Eclipsante(5.73d): Mintaka A (O9.5) y Mintaka B (B0.5)  
 $M=20M_{\odot}$   $T=33000K$   
 $L=90000 L_{\odot}$   $R=16R_{\odot}$





Sin embargo, en el cielo...

# Sin embargo, en el cielo...

Sirio (a-CMa)

Mintaka ( $\delta$ -Ori)

Betelgeuse ( $\alpha$ -Ori)

Proción (a-CMi)



# ¿Cuál les parece que es la diferencia?

- Mintaka

$(2 \times 90000 L_o / 25 L_o) \sim 7000$  veces más luminosa que  
Sirio

- pero está

$(900 \text{al} / 8.6 \text{al}) \sim 100$  veces más lejos respecto a Sirio



# Magnitud aparente

- **Magnitud aparente (m)**

- **Brillo (b) de un cuerpo “visto” desde La Tierra**
- Hiparco de Nicea (190AC-120AC) 850 est. ← Ptolomeo:  
Clasificó las estrellas en seis magnitudes:  
Magnitud 1: Top 20, Magnitud 6: Apenas visibles
- **Norman Pogson (1829-1891):**

- Una estrella  $m=1(m_1)$  es 100 veces más brillante que una  $m=6(m_6)$

$$\frac{b_1}{b_6} = 100$$

- ¿Cómo se relacionan entre sí?

# Relación entre magnitudes

- Conviene usar un factor uniforme  $k$ :

$$\frac{b_1}{b_6} = 100 \rightarrow \frac{b_1}{b_2} = k, \frac{b_2}{b_3} = k, \dots \rightarrow b_1 = k b_2, b_2 = k b_3 \dots$$

- Entonces,

$$b_1 = (k k k k k) b_6 \rightarrow \frac{b_1}{b_6} = k^5$$

Finalmente,

$$k^5 = 100 \rightarrow k = \sqrt[5]{100} = 2.51189 \rightarrow k \approx 2.5$$

Una estrella de brillo  $b_1$  es  
dos veces y media más brillante  
que una estrella de brillo  $b_2$

$$b_i \approx 2.5 b_{i+1}$$



# Relación entre brillo y magnitud

- Ahora
  - a la estrella con brillo  $b_1$  le asignamos magnitud  $m_1$
  - a la estrella con brillo  $b_2$  le asignamos magnitud  $m_2$
- ¿Cómo se relaciona el factor de brillo con la diferencia en magnitudes?

$$\text{¿ } (m_1 - m_2) \quad b_1/b_2 ?$$

- La respuesta del ojo es logarítmica:



# Relación entre brillo y magnitud

- Proponemos

$$\left( \frac{b_1}{b_2} \right) = 2.5 \rightarrow \left( \frac{b_i}{b_j} \right) = 2.5^{(m_j - m_i)}$$

- Si,  $m_i = m_j \rightarrow m_i - m_j = 0 \rightarrow b_i = b_j$
- Si,  $m_i = m_j + 1 \rightarrow m_i - m_j = 1 \rightarrow b_i = 2.5 b_j$
- Si,  $m_i = m_j - 1 \rightarrow m_i - m_j = -1 \rightarrow b_i = b_j / 2.5$
- Despejando, se puede verificar que:

$$\left( \frac{b_i}{b_j} \right) = 2.5^{(m_j - m_i)} \rightarrow (m_i - m_j) = -2.5 \log_{10} \left( \frac{b_i}{b_j} \right)$$



¿Es cierto? Veamos

Supongamos dos estrellas,  $m_i = 1$  y  $m_j = 6$

$$m_i - m_j = -2.5 \log_{10}(b_i/b_j)$$

$$\rightarrow -5 = -2.5 \log_{10}(b_i/b_j)$$

$$(-5/-2.5) = \log_{10}(b_i/b_j)$$

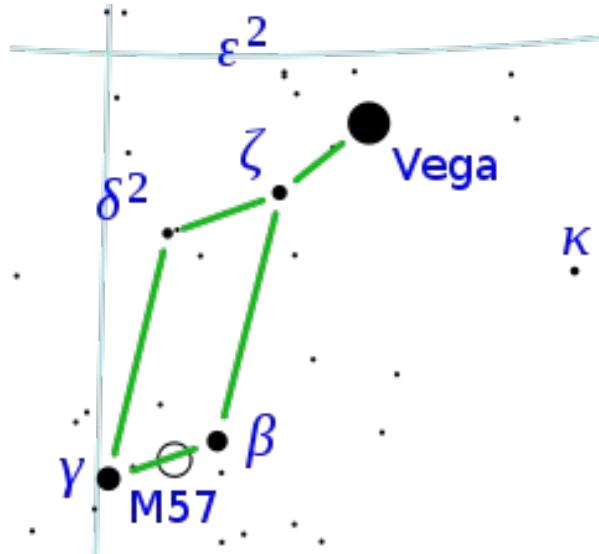
$$2 = \log_{10}(b_i/b_j)$$

$$10^2 = b_i/b_j$$

$$b_i = 100 b_j$$

**La estrella i es 100 veces más brillante que la estrella j**

# Cuando comparamos necesitamos referencias



- La escala de magnitudes es **comparativa**
- Es necesario establecer una referencia (brillo)
- **Referencia de magnitud: Estrella Vega ( $\alpha$ Lyr),  $m=0$**
- Vega, AO, blanca



# Escala moderna

-26.73 Sol (449000 veces la Luna)

-12.6 Luna llena

-6.0 Supernova del Cangrejo (SN 1054)

-4.7 Venus (máximo)

-3.0 Marte (máximo)

-1.47 Sirio (estrella más brillante)

-0.7 Canopus (2da estrella)

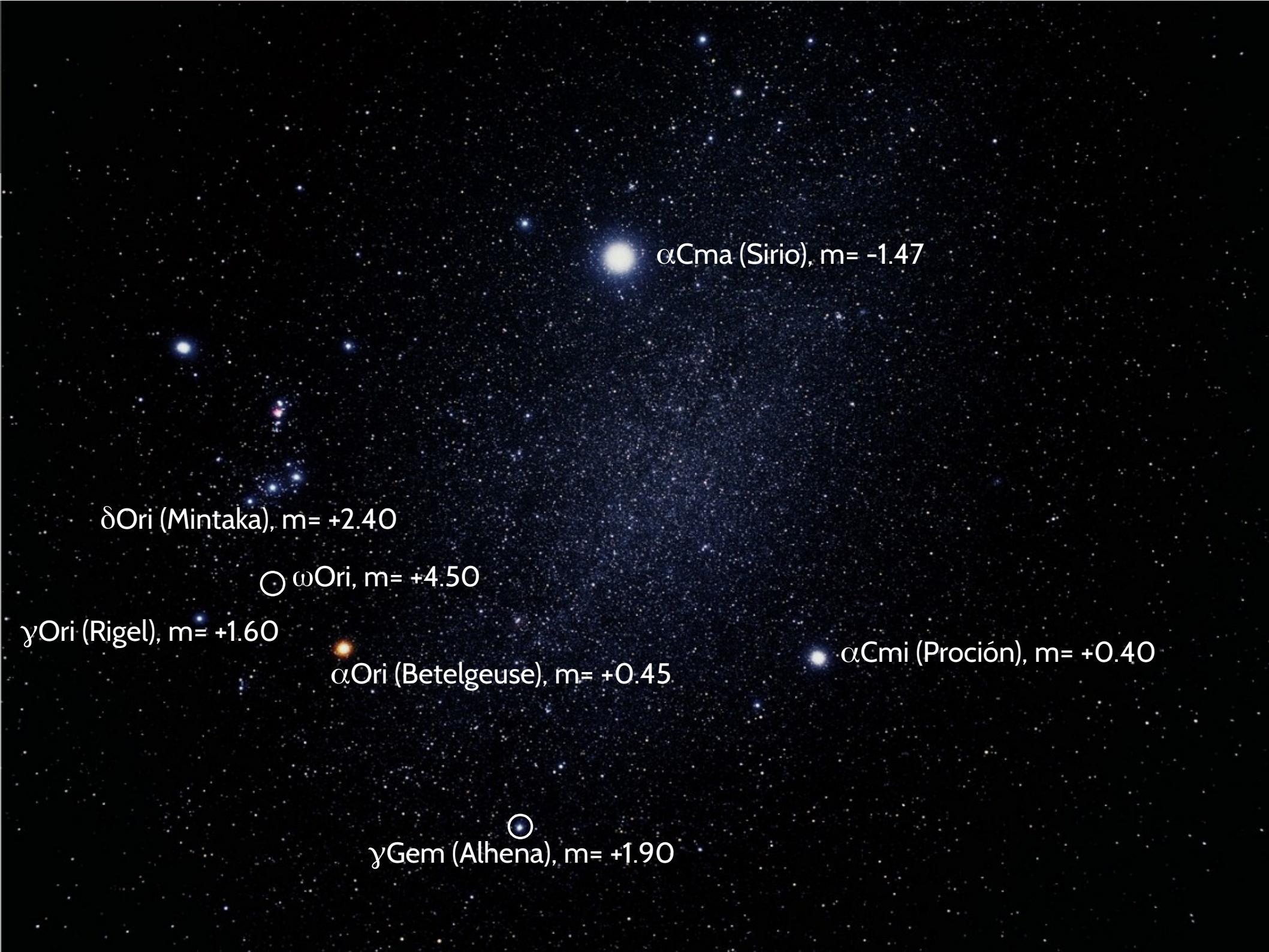
0 Vega (definición moderna)

+3 Estrellas más débiles en una ciudad

+4.6 Ganímides (Luna de Júpiter)

+6 límite de visibilidad del ojo

+30 estrellas más débiles observadas (Telescopio espacial Hubble)



$\alpha$ Cma (Sirio), m= -1.47

$\delta$ Ori (Mintaka), m= +2.40

  $\omega$ Ori, m= +4.50

$\gamma$ Ori (Rigel), m= +1.60

  $\alpha$ Ori (Betelgeuse), m= +0.45

$\alpha$ Cmi (Proción), m= +0.40

  $\gamma$ Gem (Alhena), m= +1.90



# Pero... “no todas están a la misma distancia”

- El brillo se relaciona con el flujo, y el flujo es
  - Proporcional a la luminosidad
  - Inversamente proporcional a la distancia al cuadrado
- ¿Cómo cambia la magnitud aparente de una estrella si multiplico por 10 su distancia?

# Pero... “no todas están a la misma distancia”

- Decuplicar distancia: flujo  $\rightarrow$  flujo/100 y brillo  $\rightarrow$  brillo/100

$$m_{nueva} - m_{vieja} = -2.5 \log_{10} \left( \frac{b_{nueva}}{b_{vieja}} \right)$$

$$m_{nueva} - m_{vieja} = -2.5 \log_{10} \left( \frac{b_{vieja}/100}{b_{vieja}} \right)$$

$$m_{nueva} - m_{vieja} = -2.5 \log_{10} \left( \frac{1}{100} \right)$$

$$m_{nueva} - m_{vieja} = -2.5 \times (-2)$$

$$m_{nueva} - m_{vieja} = 5$$

$$m_{nueva} = m_{vieja} + 5$$

Si aumento 10 veces la distancia de una estrella, su brillo disminuye 100 veces, y su magnitud aumenta en 5  
Si era  $m=1$ , pasa a  $m=6$



# Magnitud absoluta

- **Magnitud absoluta  $M$ , es la magnitud aparente que tendría una estrella si su distancia fuera de 10pc**
  - Relación con la magnitud aparente  $m$  y la distancia  $d$ : (medida en parsecs):

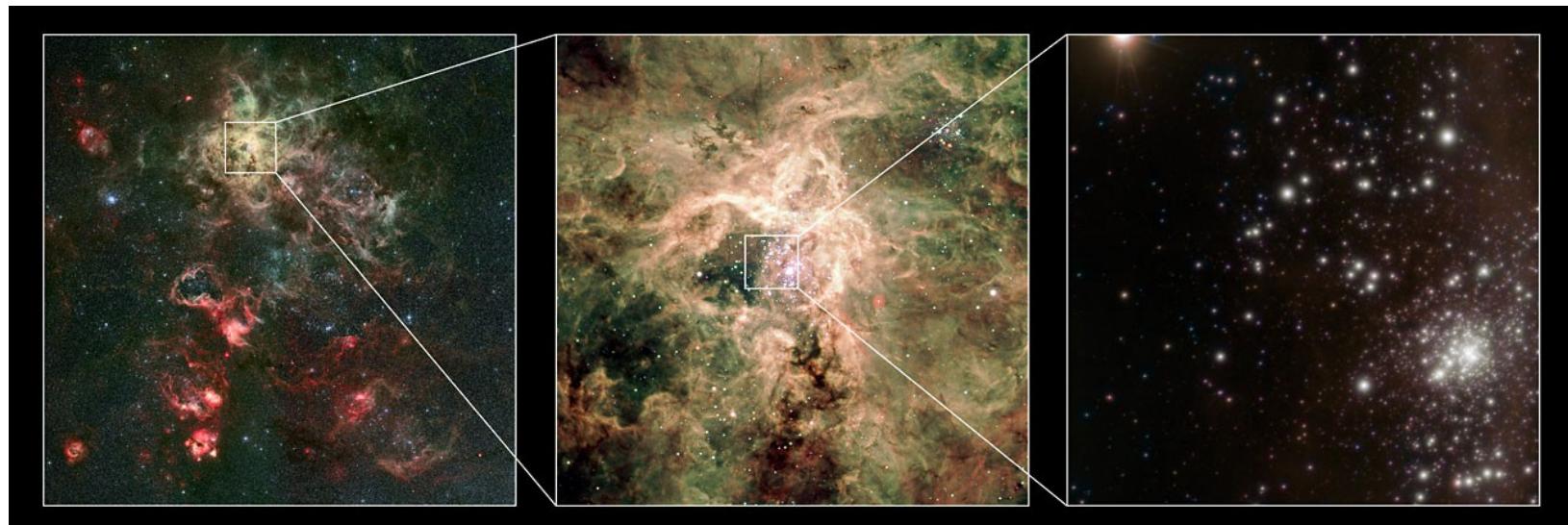
$$M = m - 5 \left( \log_{10}(d) - 1 \right)$$

- P.ej.: Si  $d=10$  pc,  $M = m - 5 [1-1] = m - 5(0) = m$
- Magnitudes absolutas y aparentes:
  - Sol:  $m=-26.73$ ,  $M=4.75$
  - Mintaka ( $\delta$ Ori):  $m=2.4$ ,  $M=-4.84$
  - Sirio (aCMa):  $m=-1.45$ ,  $M=1.44$



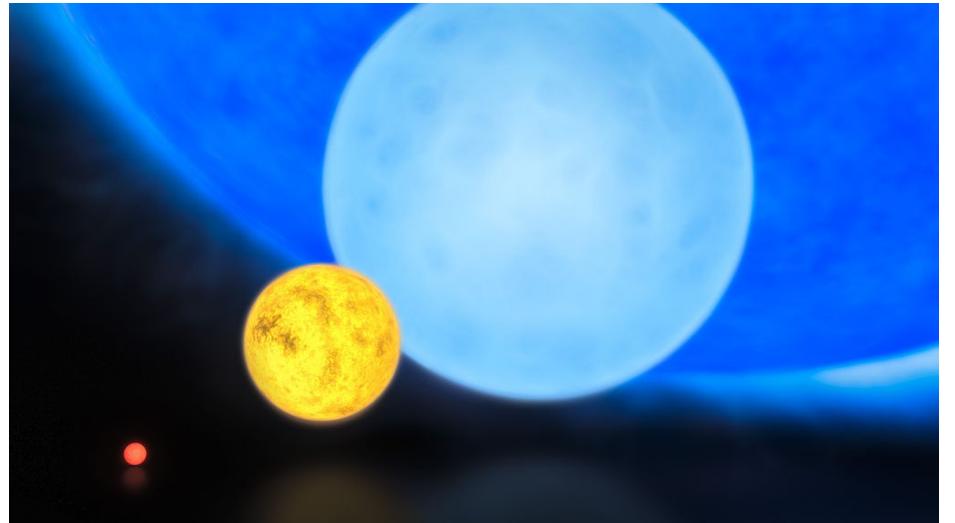
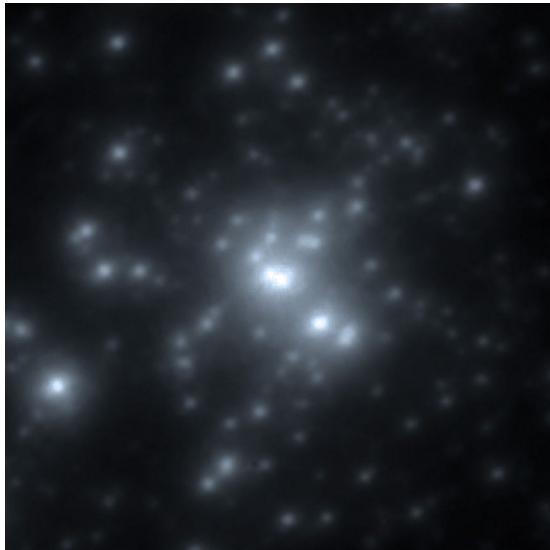
# La estrella más brillante

- R136a1 es la estrella más masiva y brillante conocida
  - Masa ~ 265 Masas solares
  - Luminosidad ~ 8.7 millones de luminosidades solares
  - Forma parte del supercúmulo estelar 30 Doradus (Nebulosa Tarántula)
  - Se encuentra en la Gran Nube de Magallanes, a 165000 al (~50000 pc)





# R136a1



- $m=12.28, M= -12.6$
- ¡Si  $d=10$  pc (32.6 al) brillaría tanto como la Luna llena!!
- Las más brillantes  
[http://en.wikipedia.org/wiki/List\\_of\\_most\\_luminous\\_known\\_stars](http://en.wikipedia.org/wiki/List_of_most_luminous_known_stars)

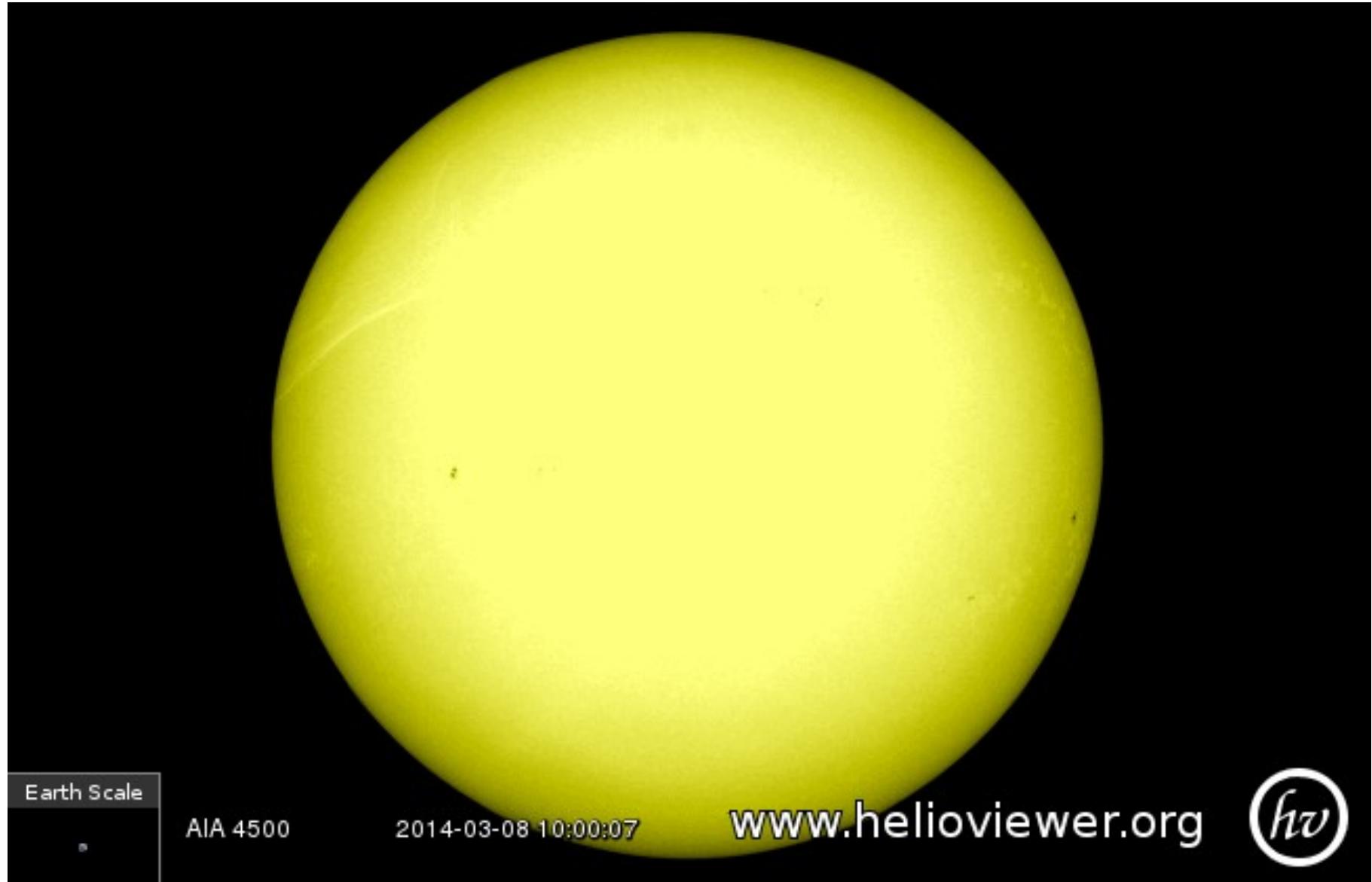


# Nuestra fuente de energía

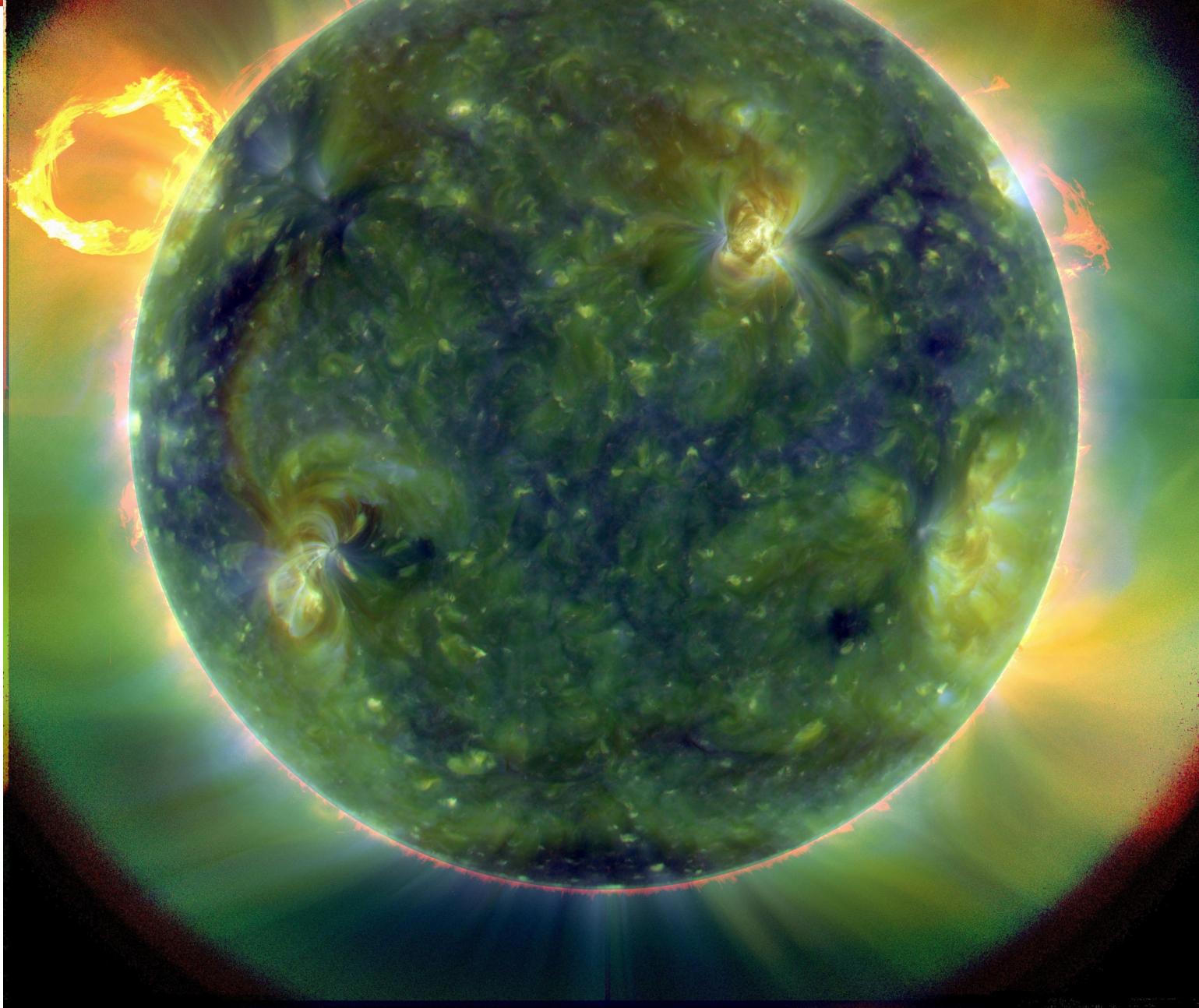




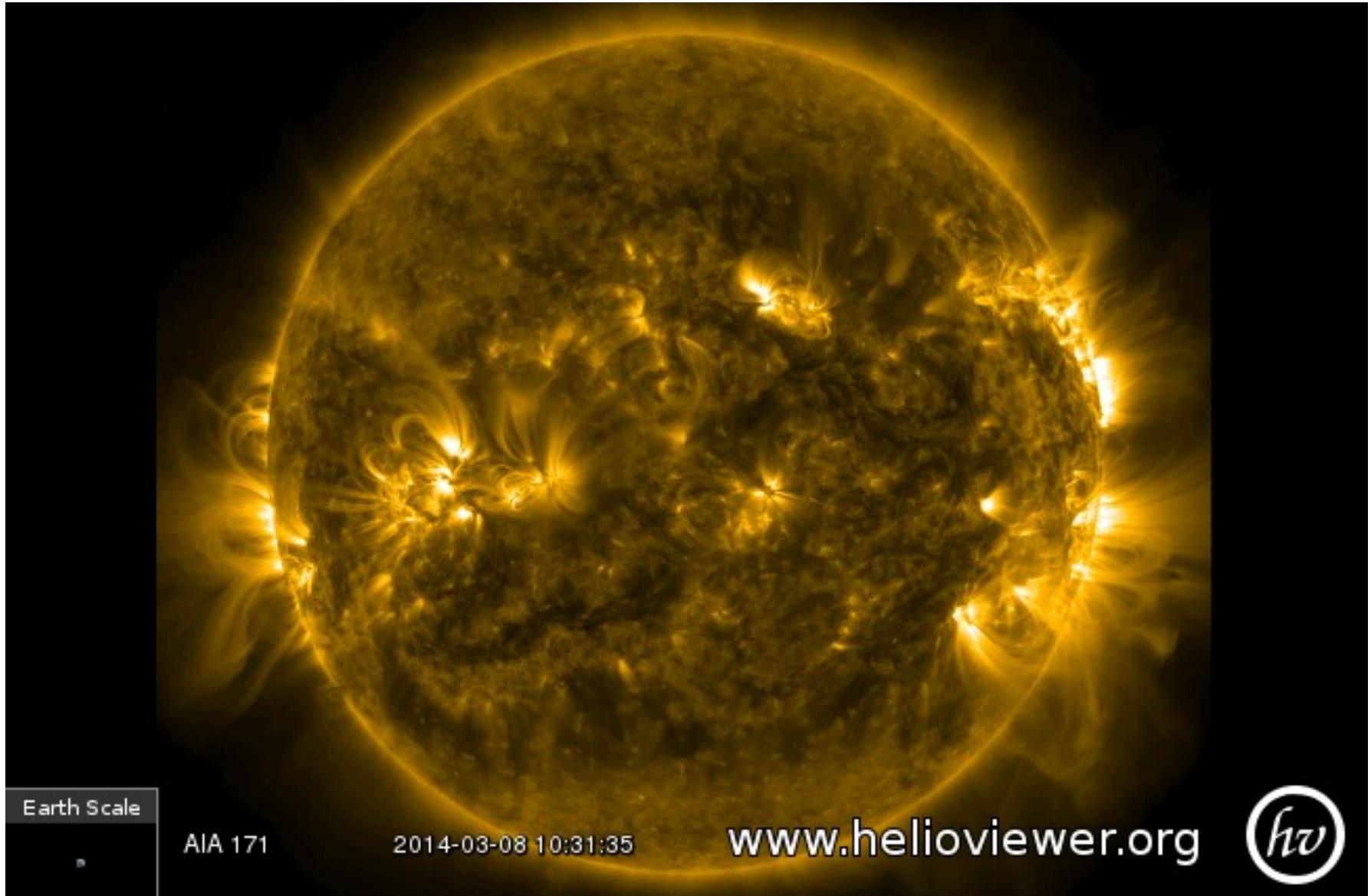
# ¿Amarillo o verde?



# Así es nuestro Sol



# Mirando en otras longitudes de onda





# Es cómodo medir las cosas en términos solares

- Masa Solar:

$$M_{\text{Sol}} = 1.989 \times 10^{30} \text{ kg} \simeq 1000 M_{\text{Júpiter}} \simeq 333000 M_{\text{Tierra}}$$

- Radio Solar:

$$R_{\text{Sol}} = 6.96 \times 10^8 \text{ m} = 696000 \text{ km}$$

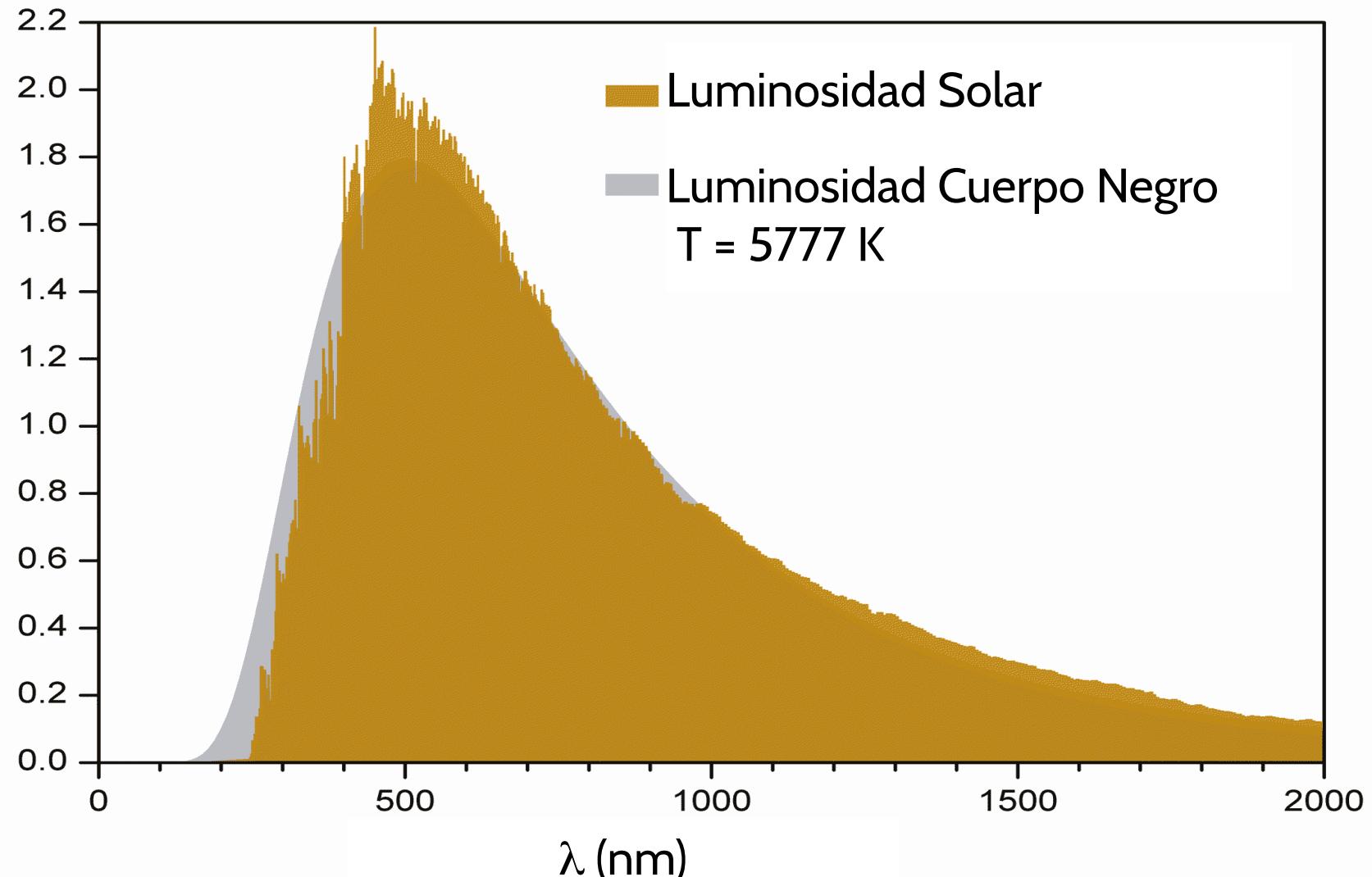
- Luminosidad Solar:

$$L_{\text{Sol}} = 3.83 \times 10^{26} \text{ W}$$

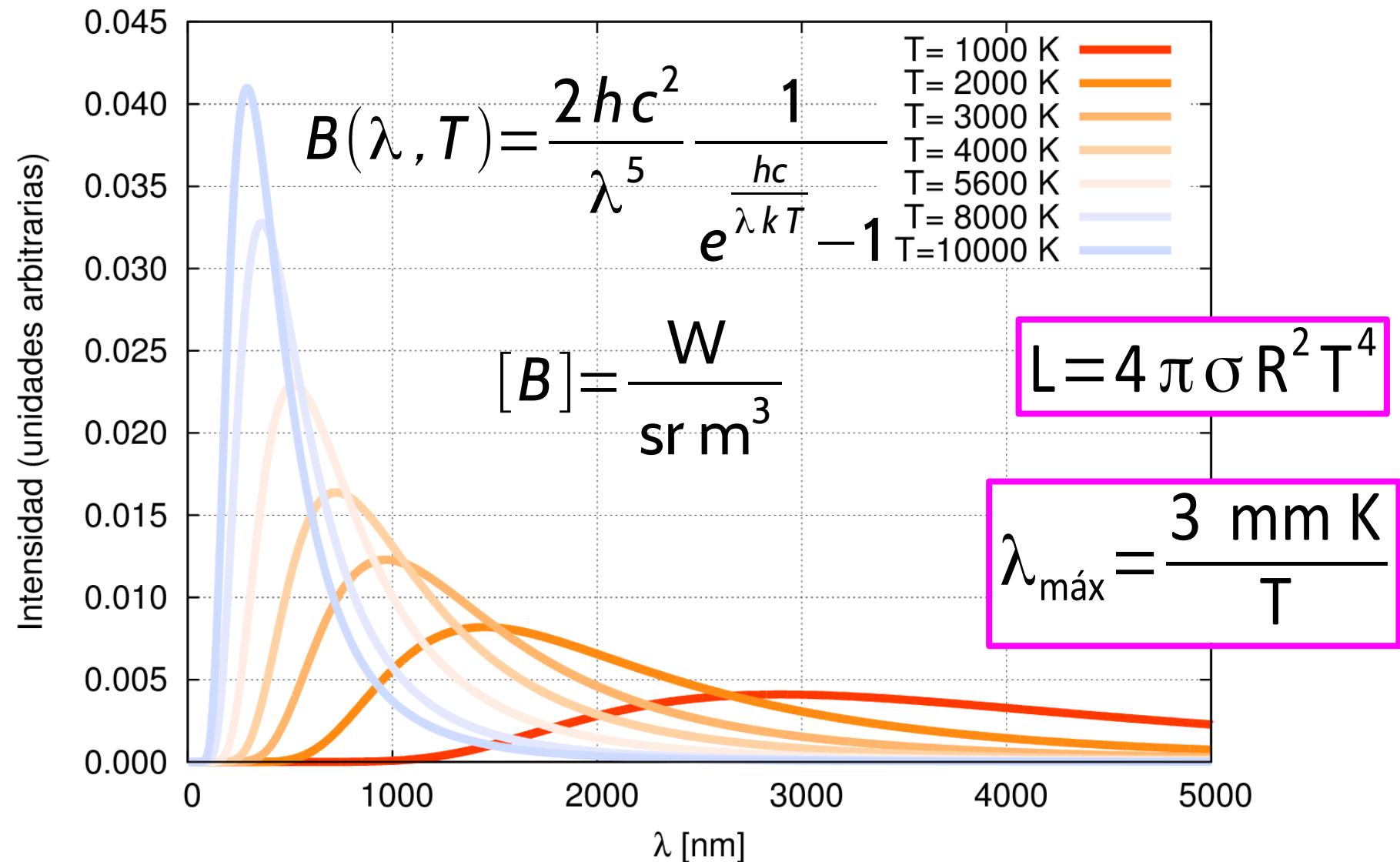
- Alto:

**1 segundo de energía liberada en el Sol  
equivale a 800000 años de consumo humano (2013)**

# El Sol como un cuerpo negro



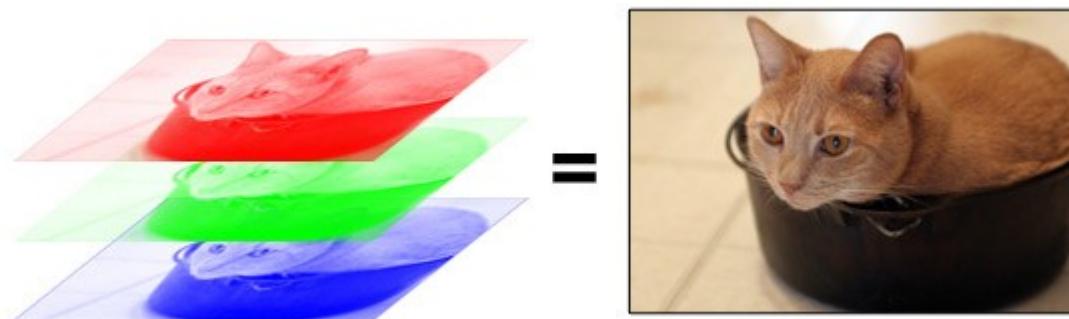
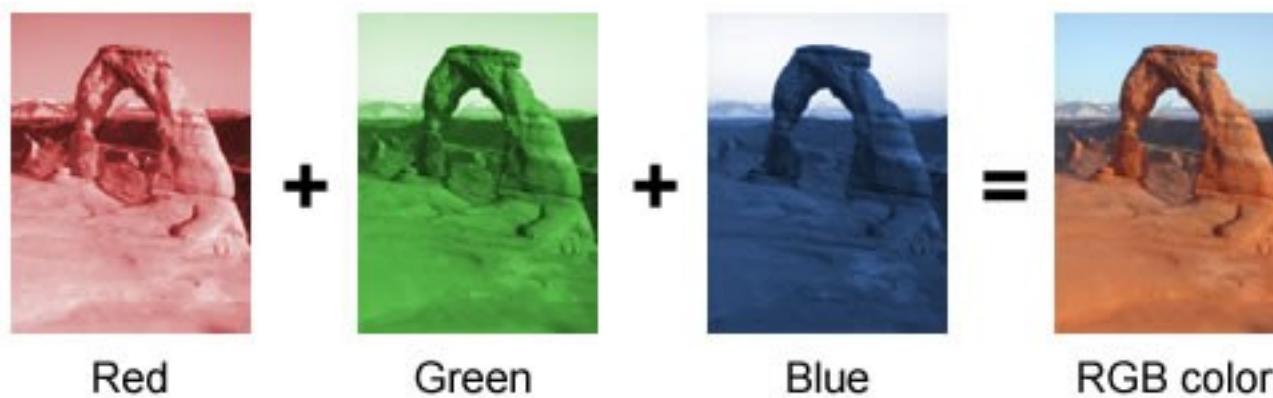
# ¿Qué ruido hace un fotón al caer? ¡Planck!





# “Color” → Temperatura

- ## • ¿Cómo cuantificar el color?

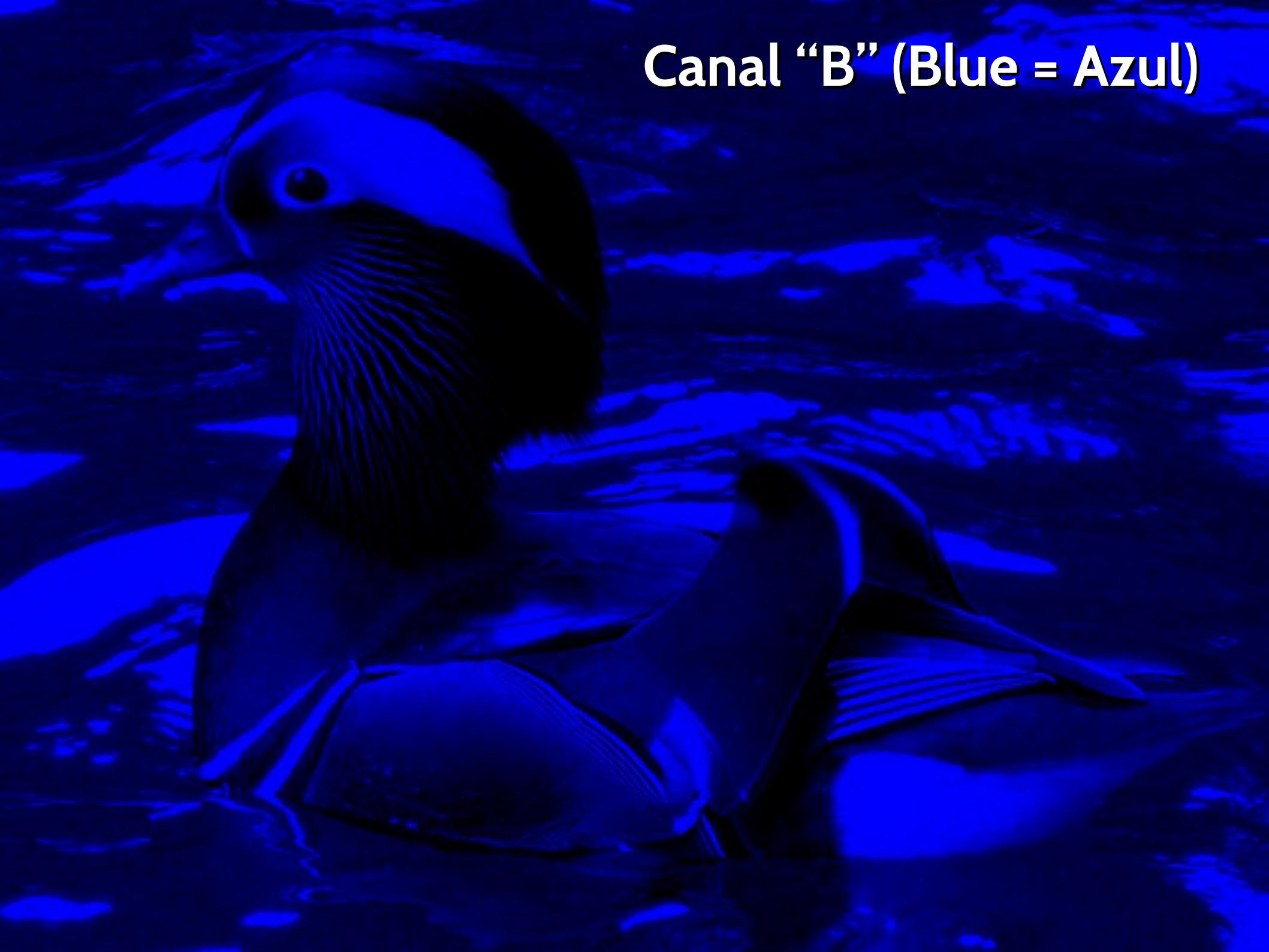




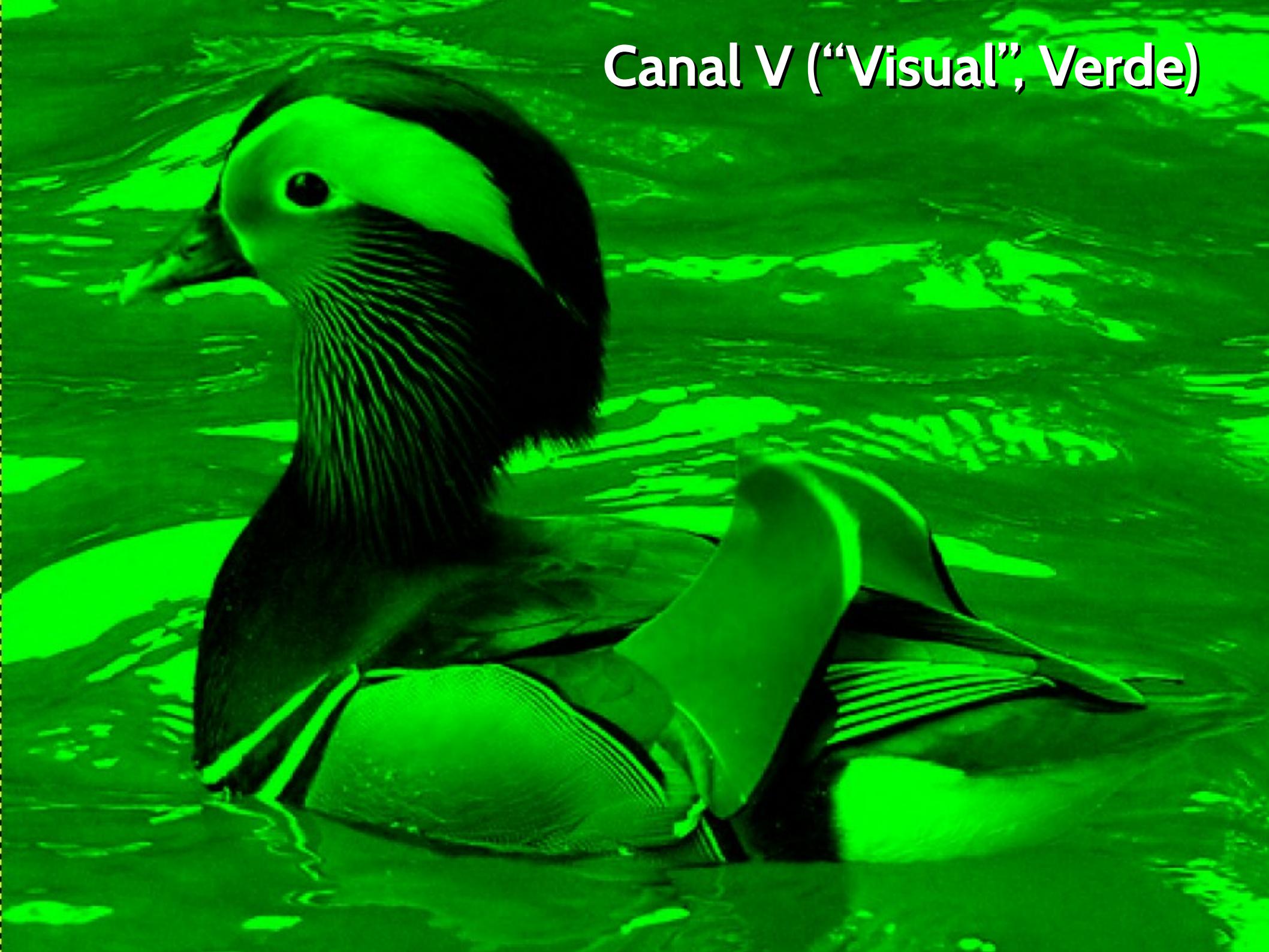
**Canal “R” (Red = Rojo)**



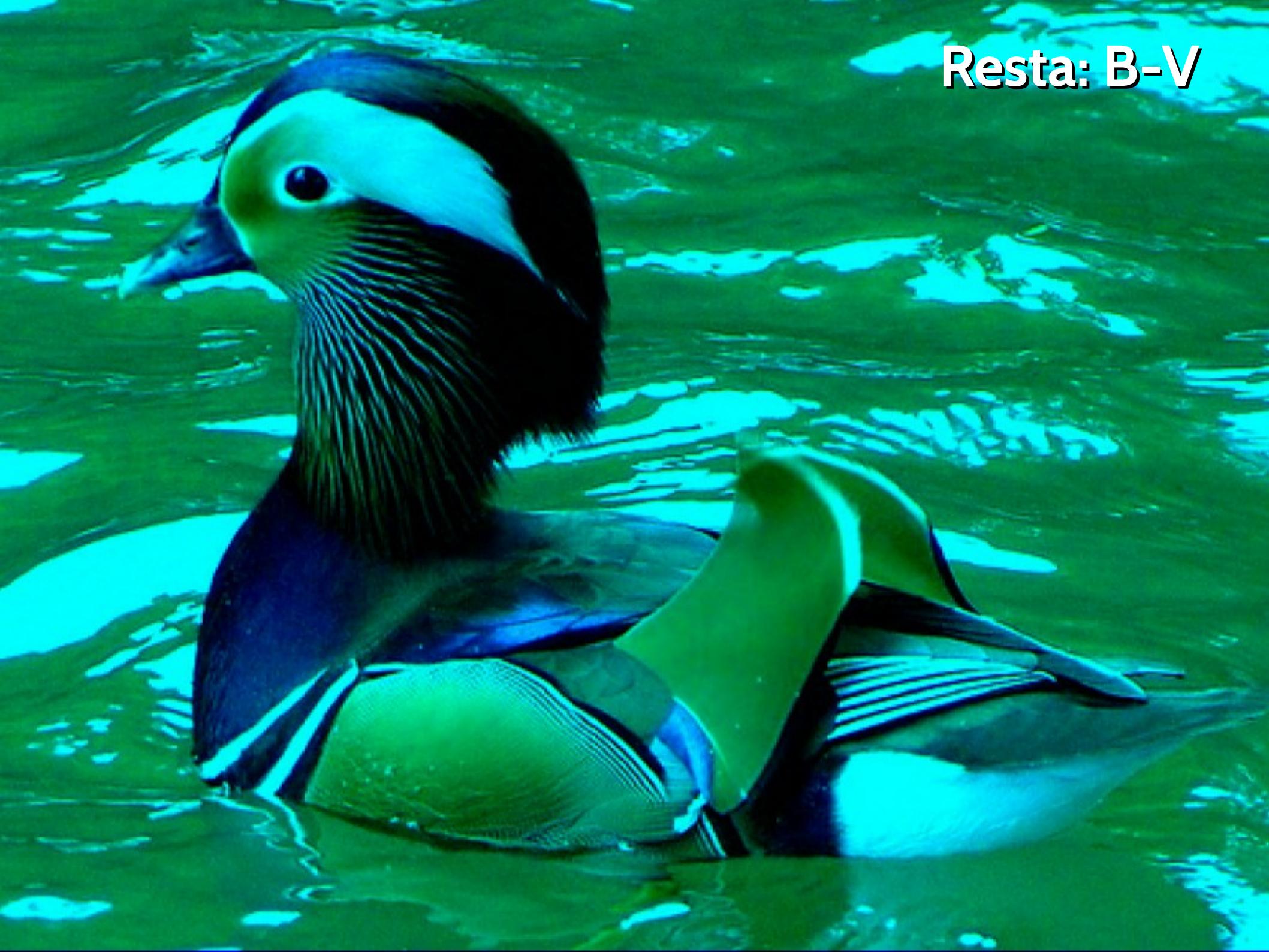
**Canal “B” (Blue = Azul)**



**Canal V (“Visual”, Verde)**



Resta: B-V

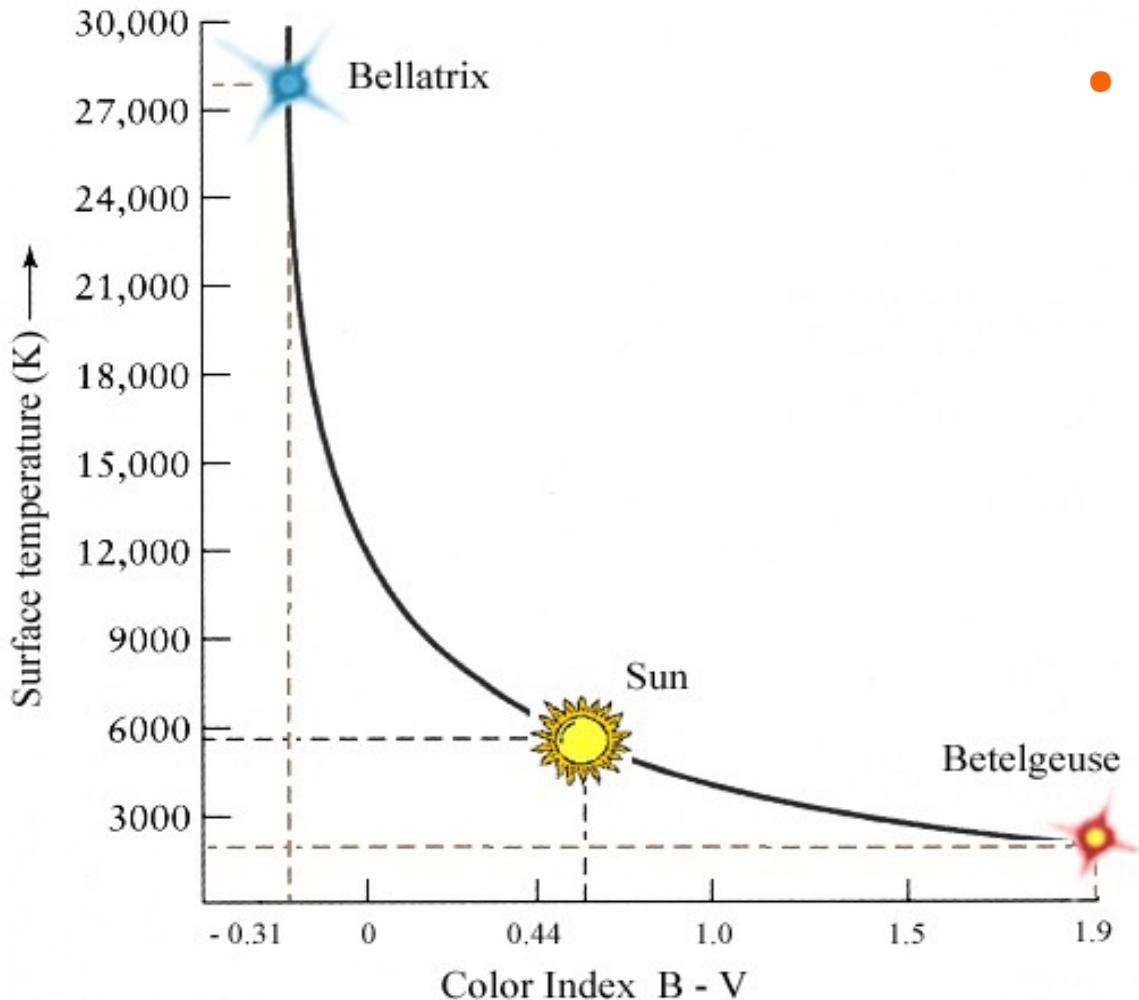




Para las estrellas → magnitudes



# Se observa que para estrellas, $B-V \rightarrow T$



- Índice  $B-V$

- $m_B$  = magnitud en el canal B
- $m_V$  = magnitud en el canal V

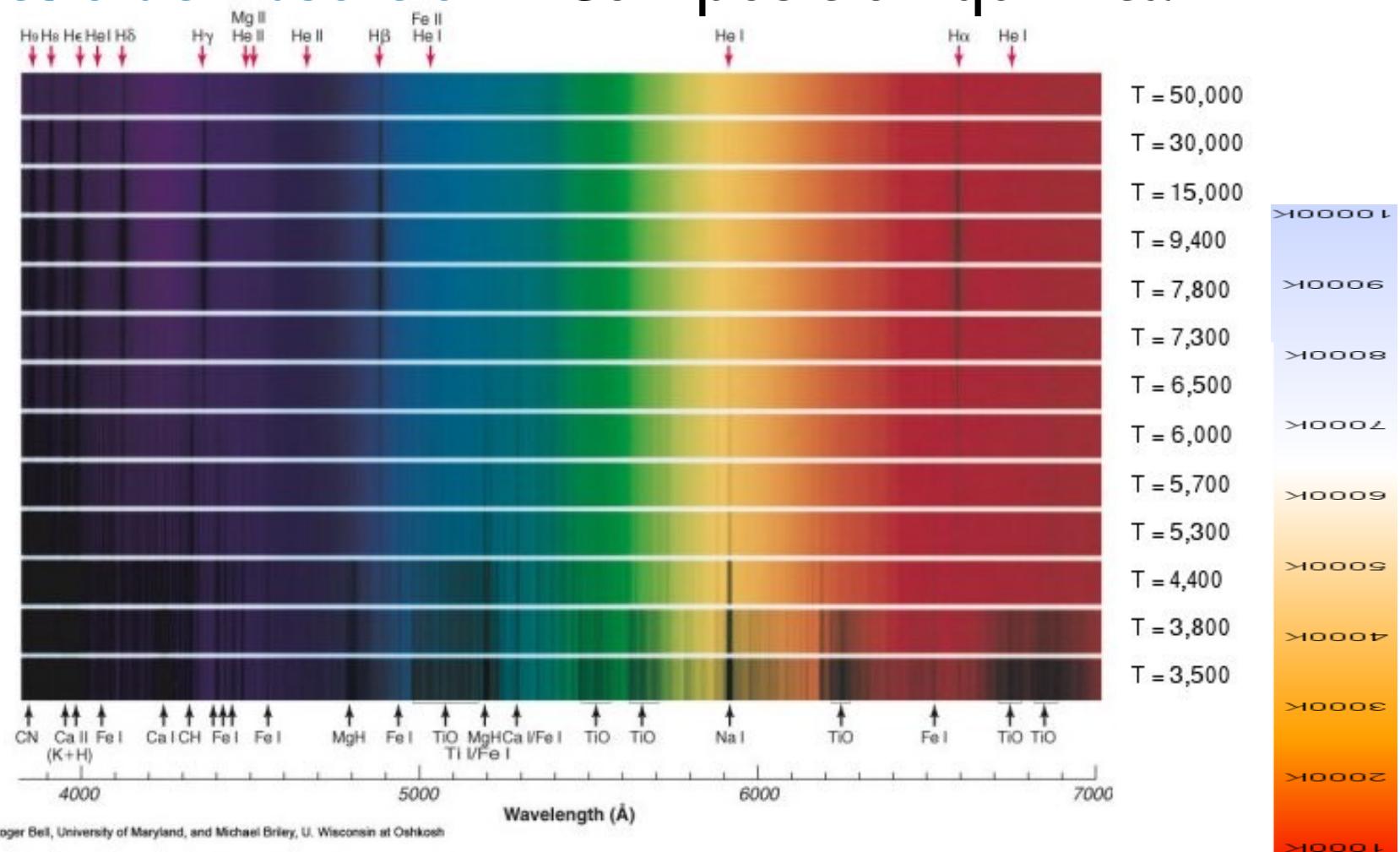
$$(B-V) = m_B - m_V$$

(Recordar que m es logarítmica)

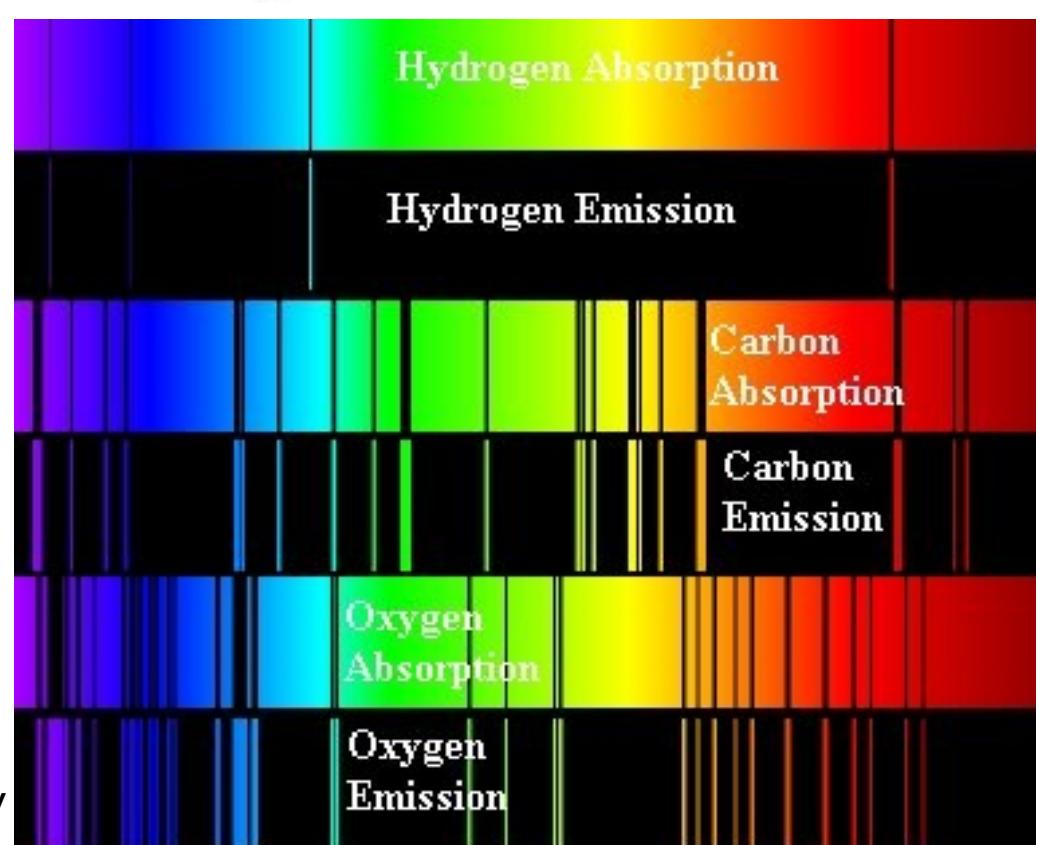
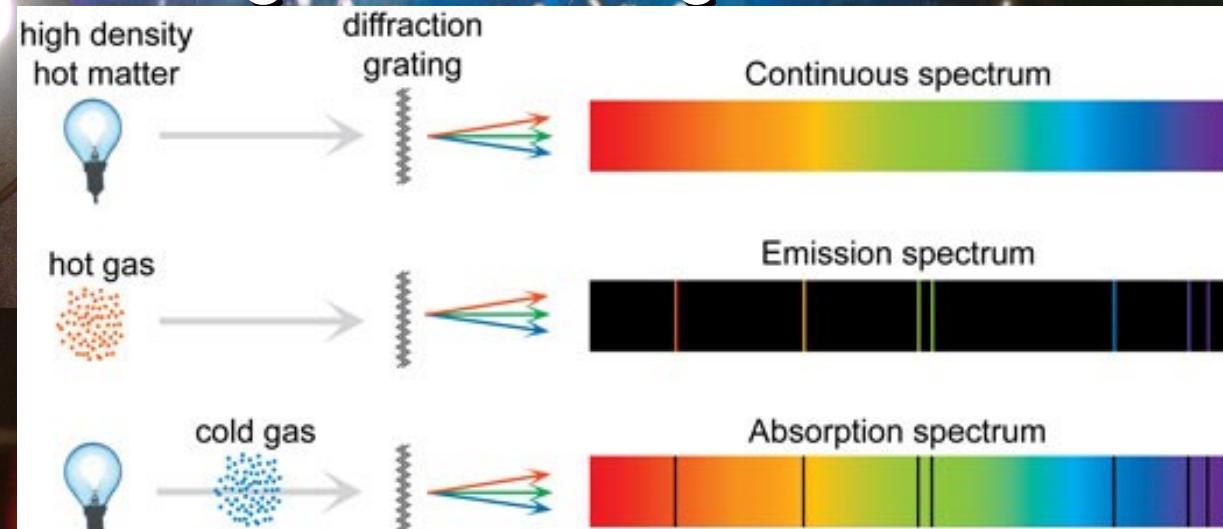
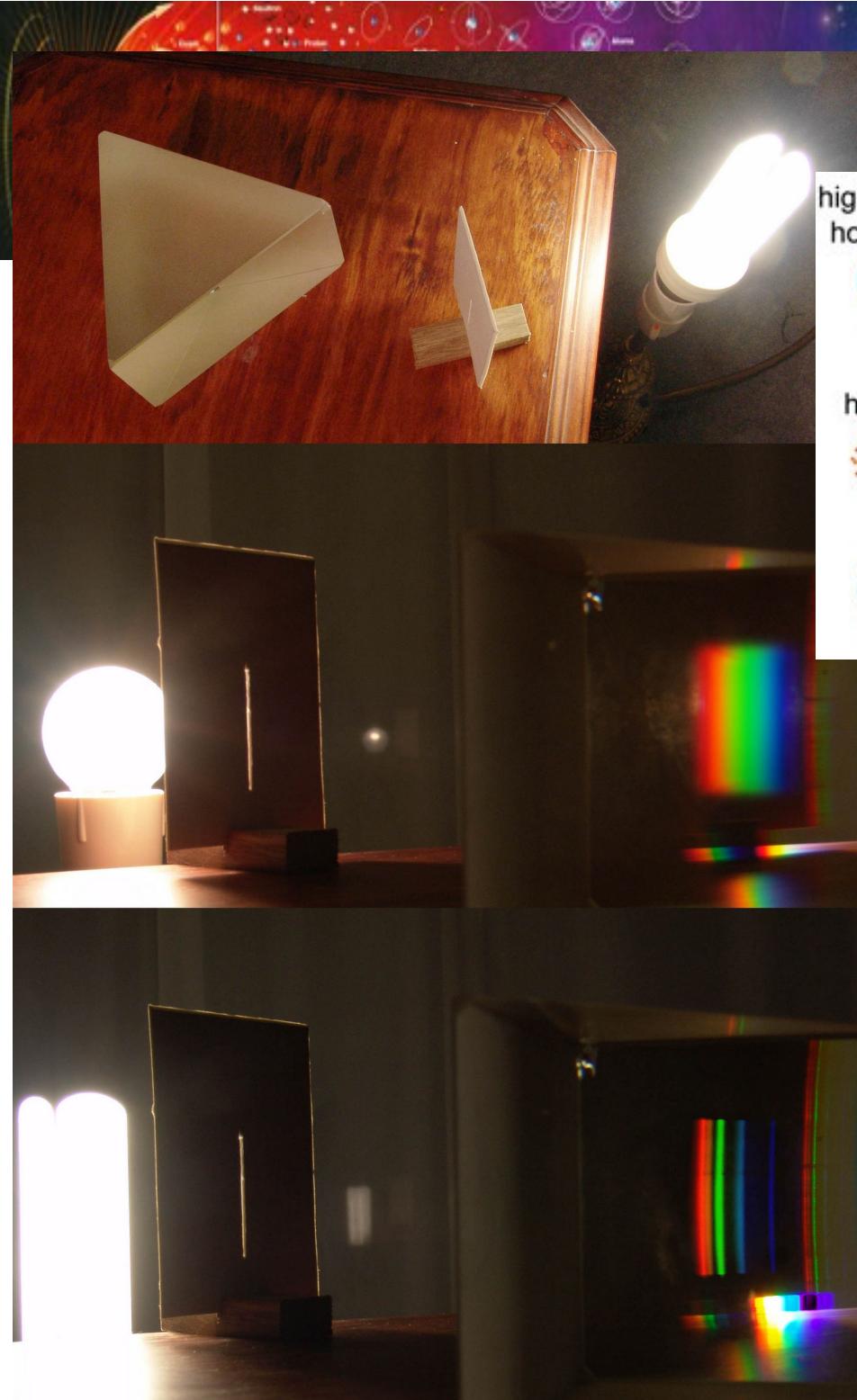
$$T = 4600 \left( \frac{1}{0.92(B-V)+1.7} + \frac{1}{0.92(B-V)+0.62} \right) K$$

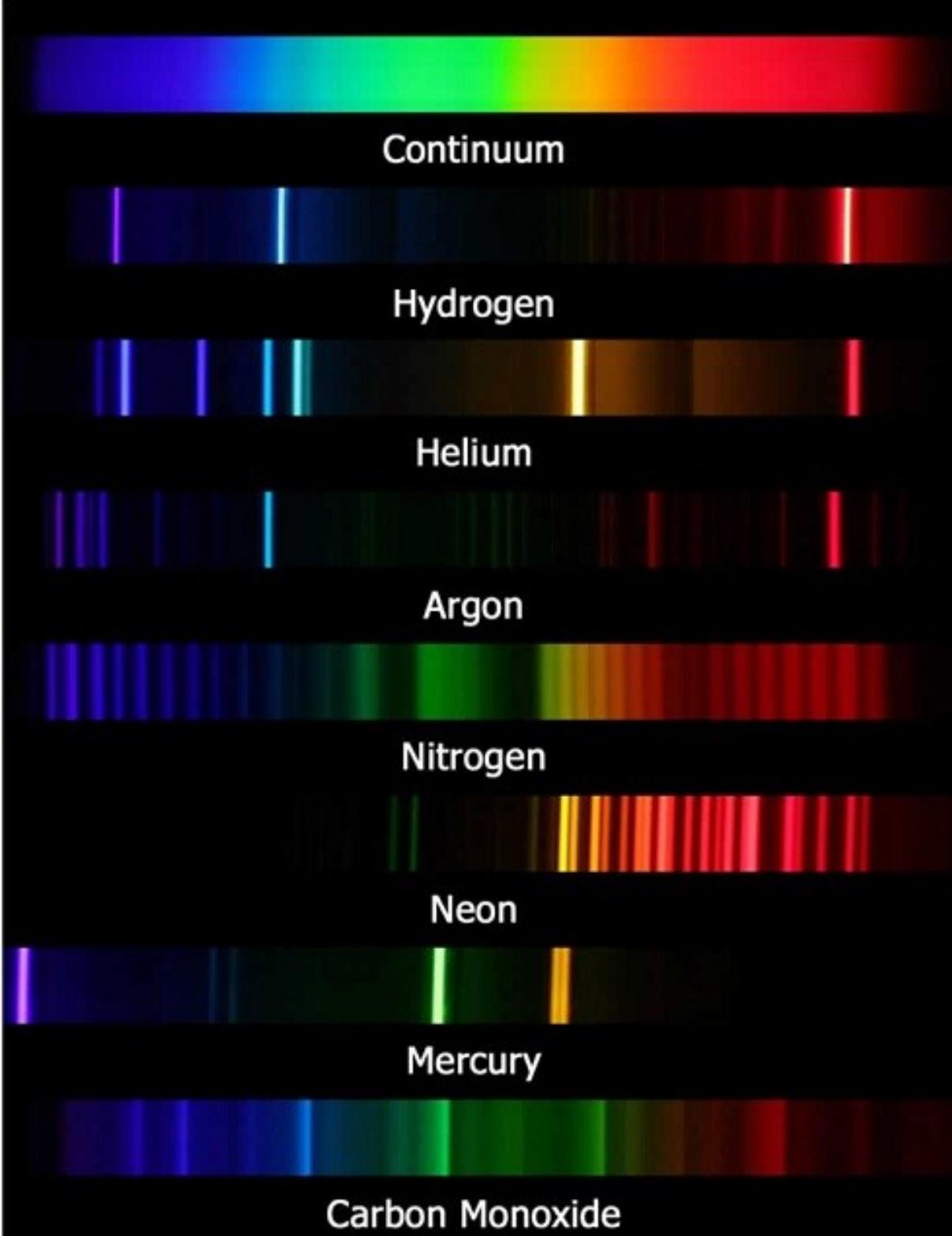
# Espectros estelares

- Emisión continua → Cuerpo Negro → Color → Temp.
- Espectro de Absorción → Composición química



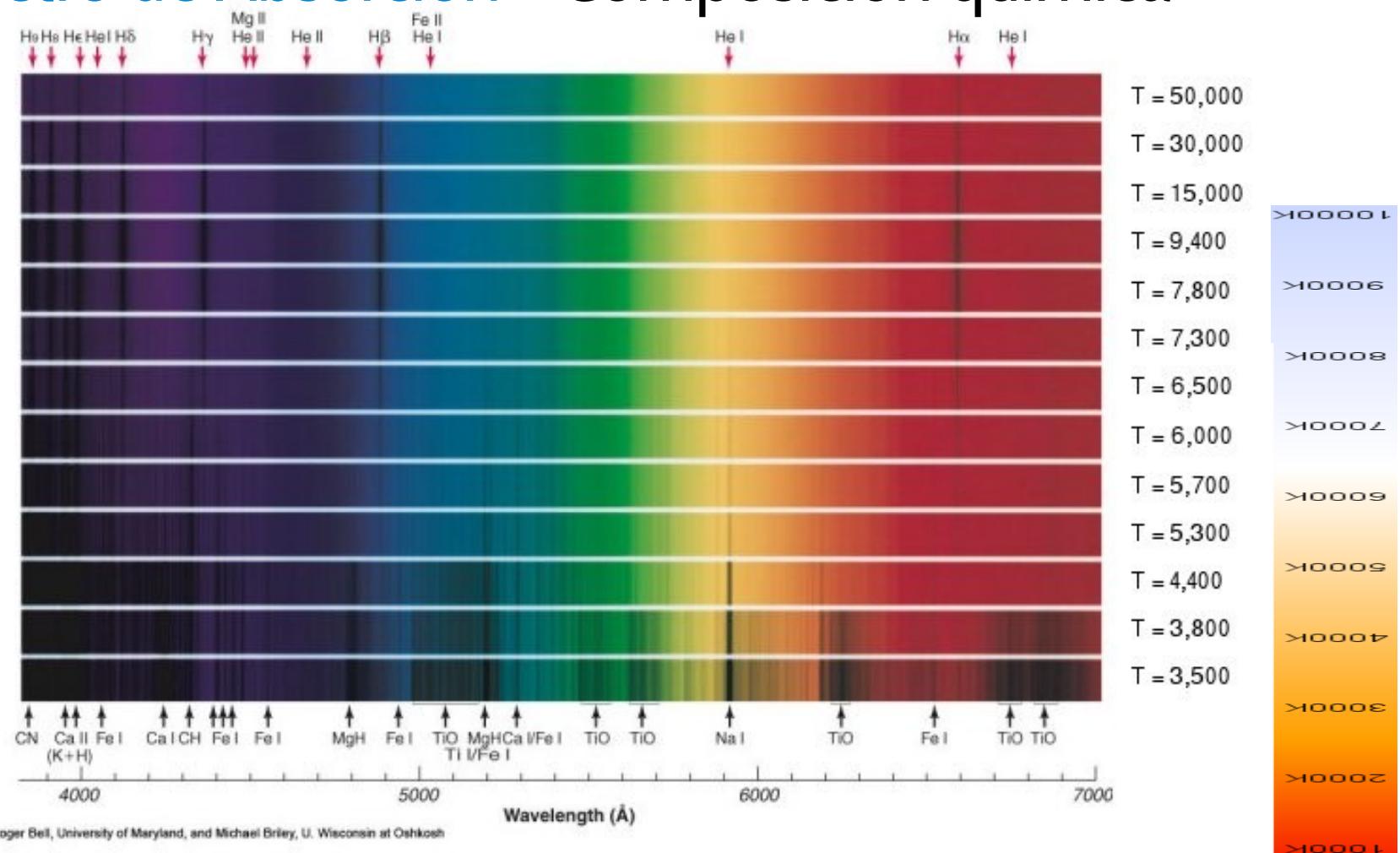
# ¿Emisión? ¿Absorción?





# Espectros estelares

- Emisión continua → Cuerpo Negro → Color → Temp.
- Espectro de Absorción → Composición química



# ¡Podemos clasificarlas!

- A B C... por temperatura superficial

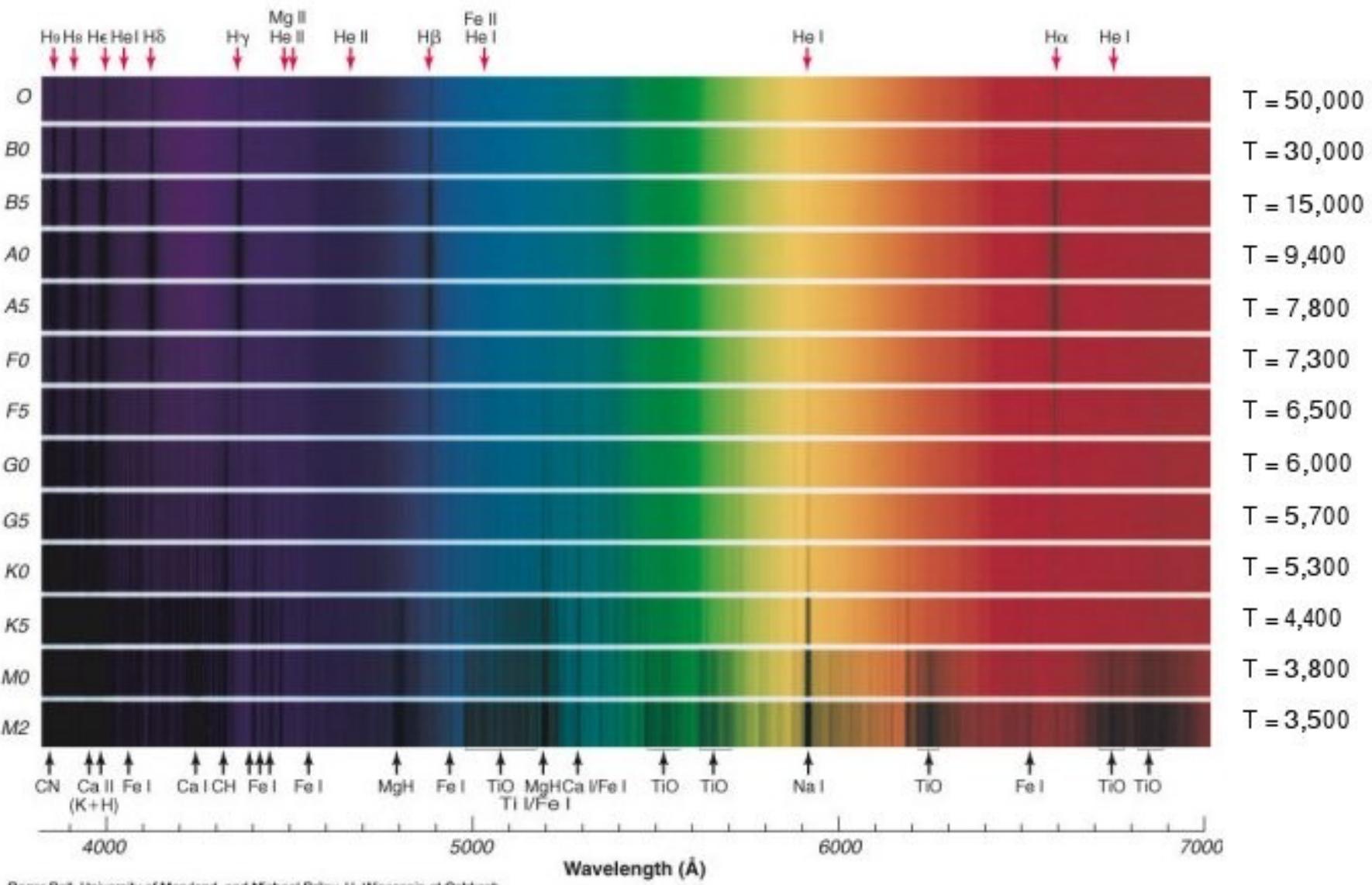
O B A F G K M R N S

- Oh Be A Fine Girl and Kiss Me Right Now Sweet
- Oh Besame Amor, Fasinadora Gitana, Kilómetros Median Rompiendo Nuestros Sueños

Cada clase se divide en 10 subclases, numeradas de 0 a 9

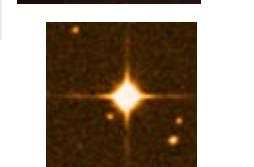


# Clasificación espectral



Roger Bell, University of Maryland, and Michael Briley, U. Wisconsin at Oshkosh

# Algunos ejemplos

Todo expresado en unidades solares (Radio, Masa, Luminosidad)			
O Azul; T > 33000 K	M > 16; R > 7; L > 30000	Mintaka (d-Ori)	
B Blanco Azulado; 10000<T<30000K	2 < M < 16; 2 < R < 7; 25 < L < 30000	Rigel (b-Ori)	
A Blanco; 7500<T<10000 K	1.4 < M < 2; 1.4 < R < 2; 5 < L < 25	Sirio (a-CMa)	
F Blanco Amarillento 6000<T<7500 K	1.04 < M < 2; 1.1 < R < 1.4; 1.5 < L < 5	Canopus (a-Car)	
G Amarillo 5200<T<6000 K	0.8 < M < 1.04; 0.9 < R < 1.1; 0.6 < L < 1.5	Sol (el nuestro)	
K Naranja 3700<T<5200 K	0.5 < M < 0.8; 0.7 < R < 0.9; 0.08 < L < 0.6	Arturo (a-Boo)	
M Rojas T<3700 K	M < 0.5; R < 0.7; L < 0.08	Gliese 581 (Lib)	



# ¿Qué define todo?

- **Relaciones entre parámetros:**

- Luminosidad (L)
- Masa (M)
- Temperatura (T)
- Radio (R)

$$L = \frac{\Delta E}{\Delta t} = 4\pi\sigma R^2 T^4$$

$$\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

- **¿Cuál es el más importante en condiciones normales?**

- **Cantidad de materia → Masa**
- Está fijada por condiciones externas → Nacimiento

# Para entender la estrella

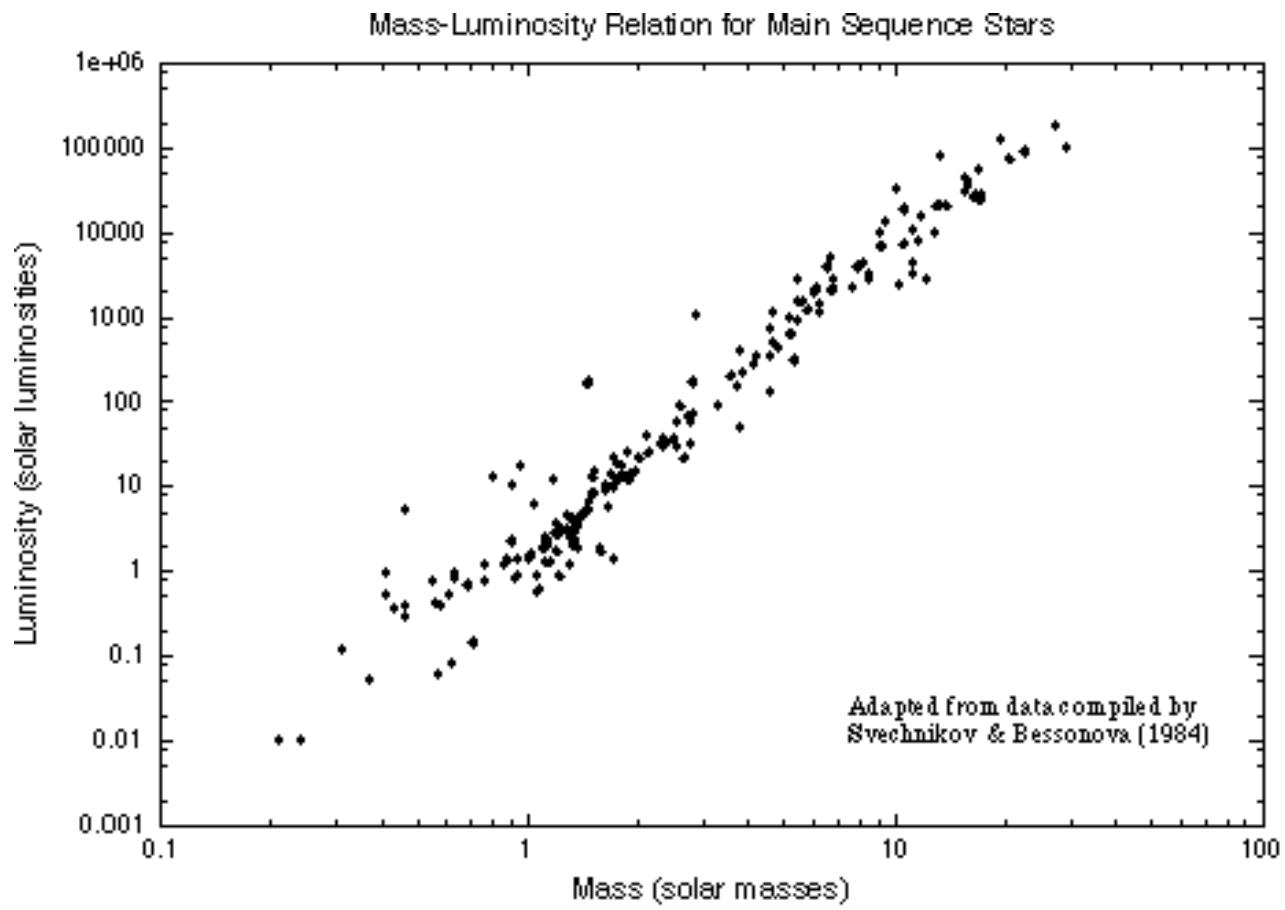
- Debemos averiguar estos parámetros:
  - Temperatura (T), Luminosidad (L), Radio estelar (R), Masa (M)



# Luminosidad → Masa

- Si:  $(0.1 < \text{Masa Estelar} < 50)$  masas solares:  
**L es proporcional a la  $M^4$**
- Nota: En general,  $M^a$ , con a entre 3 y 4 (~ masa)

$$\left( \frac{L_{\text{Estrella}}}{L_{\text{Sol}}} \right) = \left( \frac{M_{\text{Estrella}}}{M_{\text{Sol}}} \right)^4$$



Luminosidad → Masa

## Mass-Luminosity Relationship

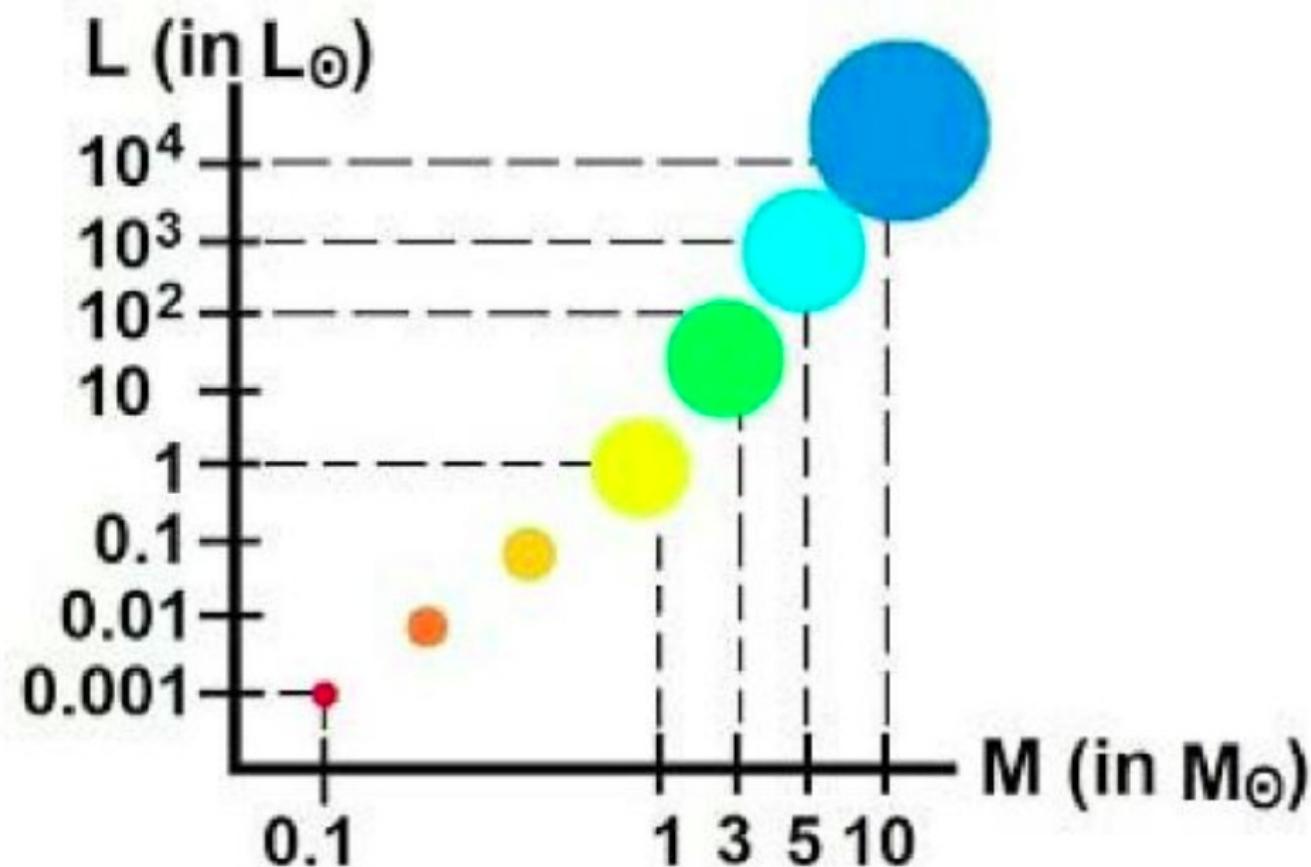


Fig. 2 Schematic representation of the mass-luminosity relation. Source: Astronomy – Ch. 17: The Nature of Stars: Mass-Luminosity Relationship