Stellar Evolution:
a Journey
through the H-R Diagram

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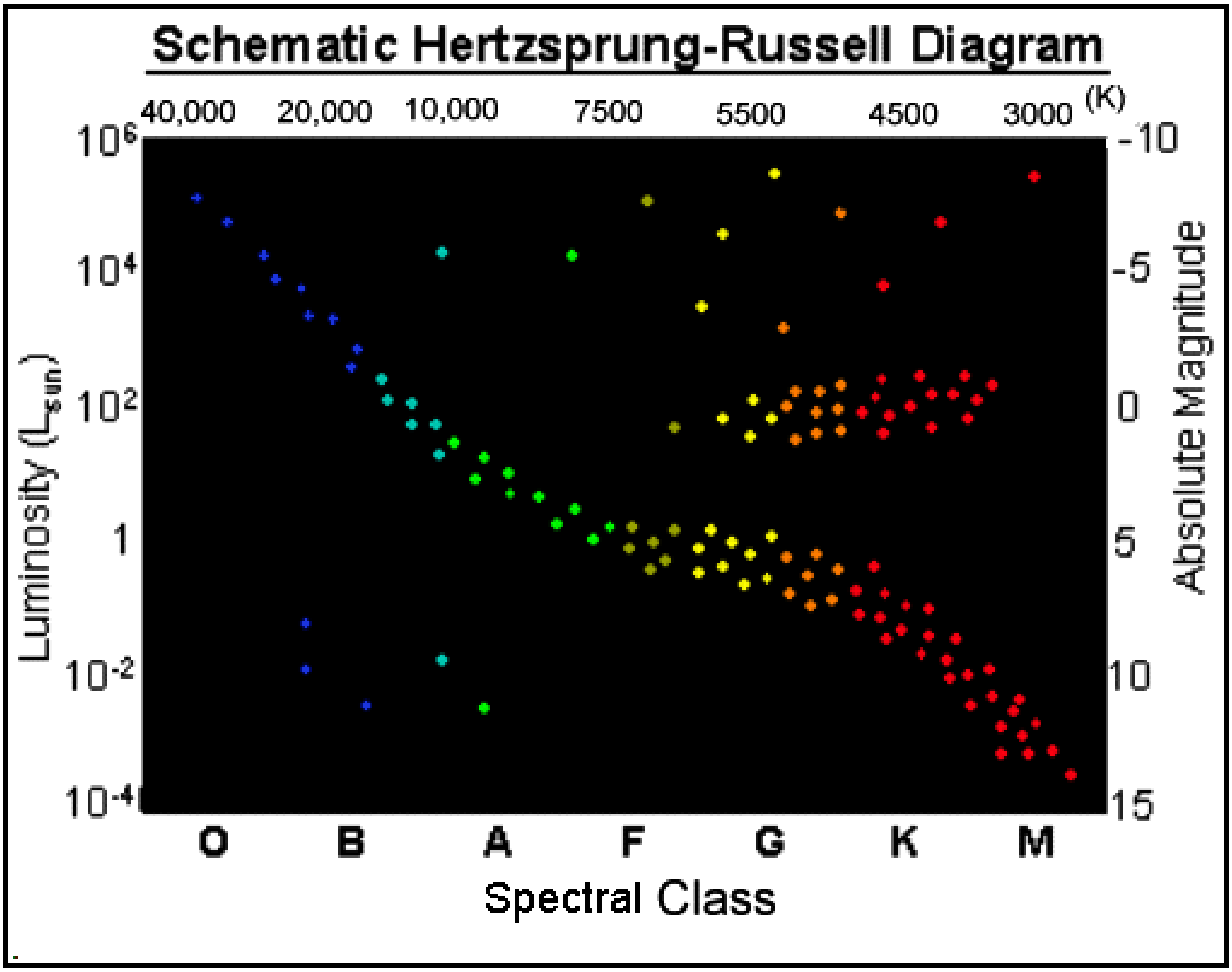

Schematic Hertzsprung-Russell Diagram
40,000
20,000
10,000
7500
5500
4500
3000
(K)
10^6
10^4
10^2
1
10^-2
10^-4
Luminosity (L_sun)
-10
-5
0
5
10
15
Absolute Magnitude
O
B
A
F
G
K
M
Spectral Class

The Herztsprung-Russell Diagram (HRD) was independently invented by Herztsprung (1911) and Russell (1913)

They plotted stars' absolute luminosity (magnitude) versus their temperature (color). Hence, these diagrams are also known as color-magnitude diagrams (CMD's)

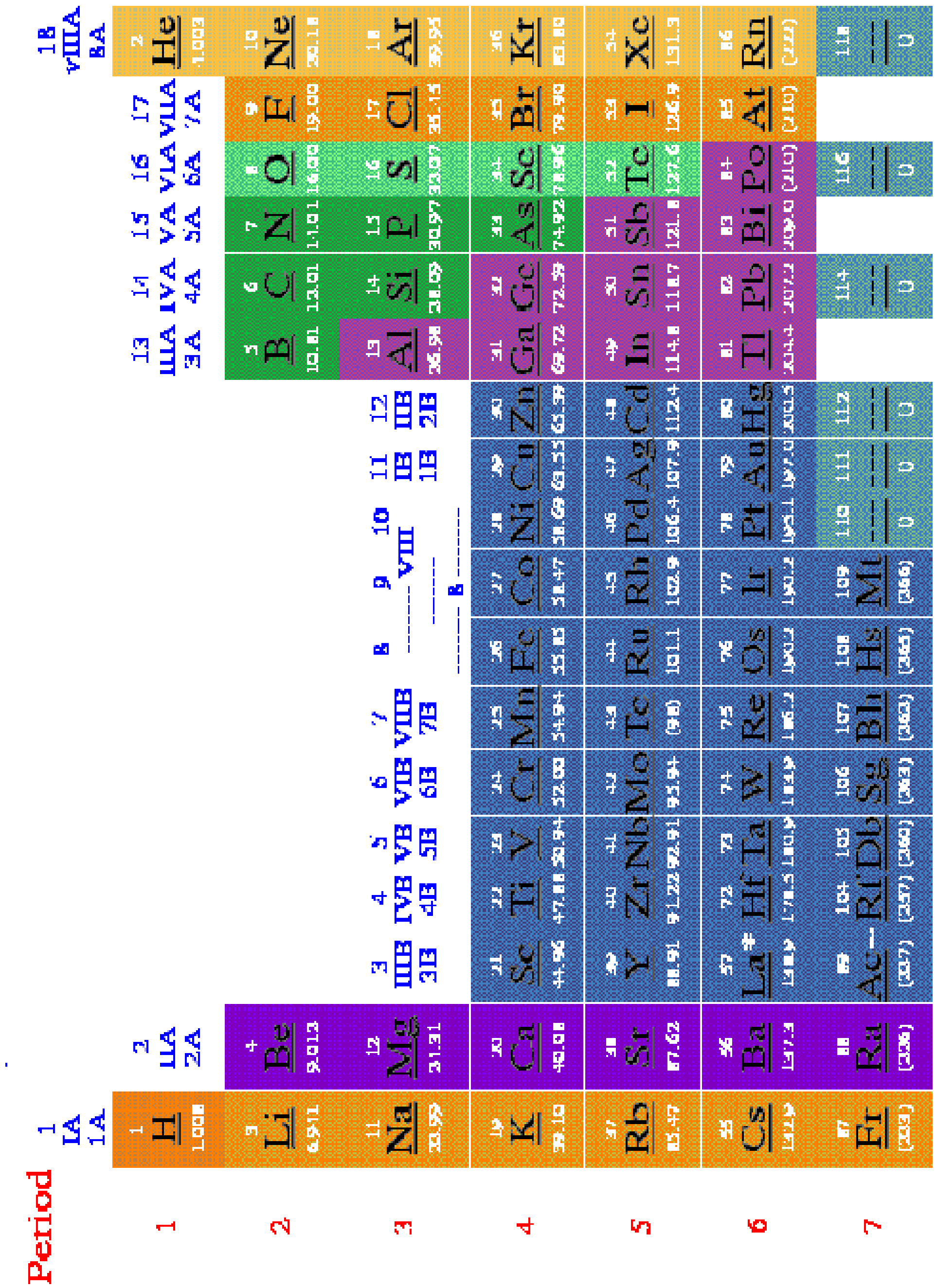
They obtained an empirical result–more than 20 years would be required to fully explain it.

The H-R diagram is a fundamental empirical result about the properties of stars, much like the periodic table of the elements was for chemistry:

- chemical elements grouped by similar properties

- previously unnoticed group properties emerged

- theoretical explanation had to wait for many decades (quantum mechanics)



Mendeleev (in 1869) grouped the 65 known elements according to their valency and atomic weight

The final explanation came 50 years later with the development of Quantum Mechanics:

- atoms react with one another by sharing the electrons in their outer shell
- different atoms have different numbers of electrons in their outer shell
- the mass of an atom is determined by the number of neutrons and protons in its nucleus

Astronomy was in much the same state at this time...

Lord Kelvin had applied the laws of gravitation, hydrostatics, and ideal gases to deduce that the Sun must be about 10 million degrees in its center. But he had difficulty identifying the energy source of the Sun:

$\rightarrow$ chemical reactions have too little energy, enough for $\sim$ 2000 years

$\rightarrow$ gravitational contraction of Sun could provide $\sim$ 50 million years worth of energy

From geology, scientists believed the Earth was at least a hundred million years old, so gravitational contraction was already on shaky ground.

Back to H-R diagram (circa 1912) . . .

Most stars lie on the "Main Sequence". Since the only known source of energy for stars was gravitational contraction, it was thought that the Main Sequence simply represented different evolutionary stages of stars:

- when stars form they have high luminosity and are hot so they are in the upper left of the H-R diagram

- they evolve by contracting, and in the process become cooler and less luminous, moving toward the lower right-hand corner

Thus, "early-type" stars are on the left (hotter), while "late-type" stars are on the right (cooler).

Although the theory has died, this terminology is still in use today!

Enter 20th century physics:

- Rutherford's discovery of the nucleus (1911)
- Gamow discovered "tunnelling" effect
- Bethe and Critchfield described the pp chain
- Weizsäcker and Bethe (independently) discovered the CNO cycle

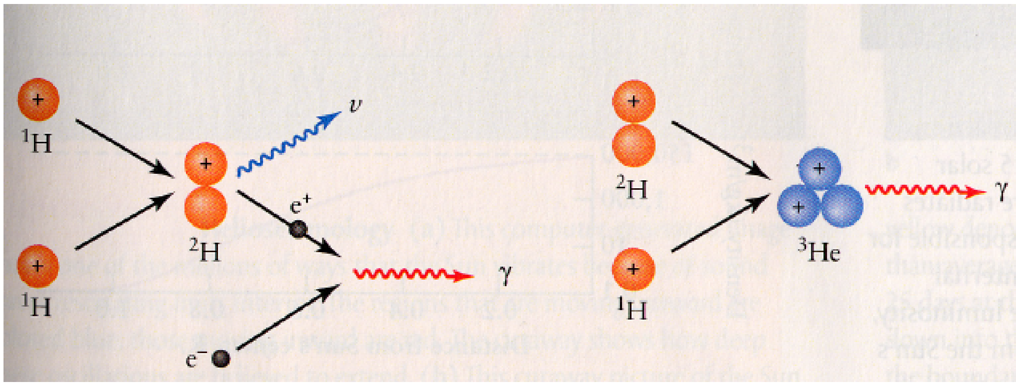
Finally there was a way that hydrogen, the most abundant element in the universe, could be turned into helium, with a resulting *huge* release of energy
$\rightarrow$ stars could shine!

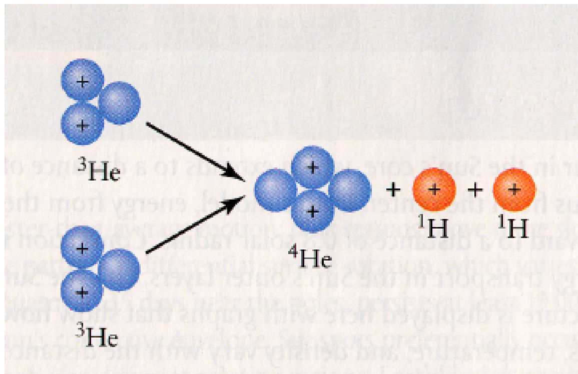
Understanding how and why stars occupy certain positions on the H-R diagram is essentially the story of understanding physics in a stellar context

The key points are:

- stars support themselves against gravity because they are hot in their centers
- the heat comes from the energy released in thermonuclear reactions
- the energy diffuses from the core to the surface and is emitted into space
- this configuration is stable so long as there is an energy source in the stellar core

How does fusion work?

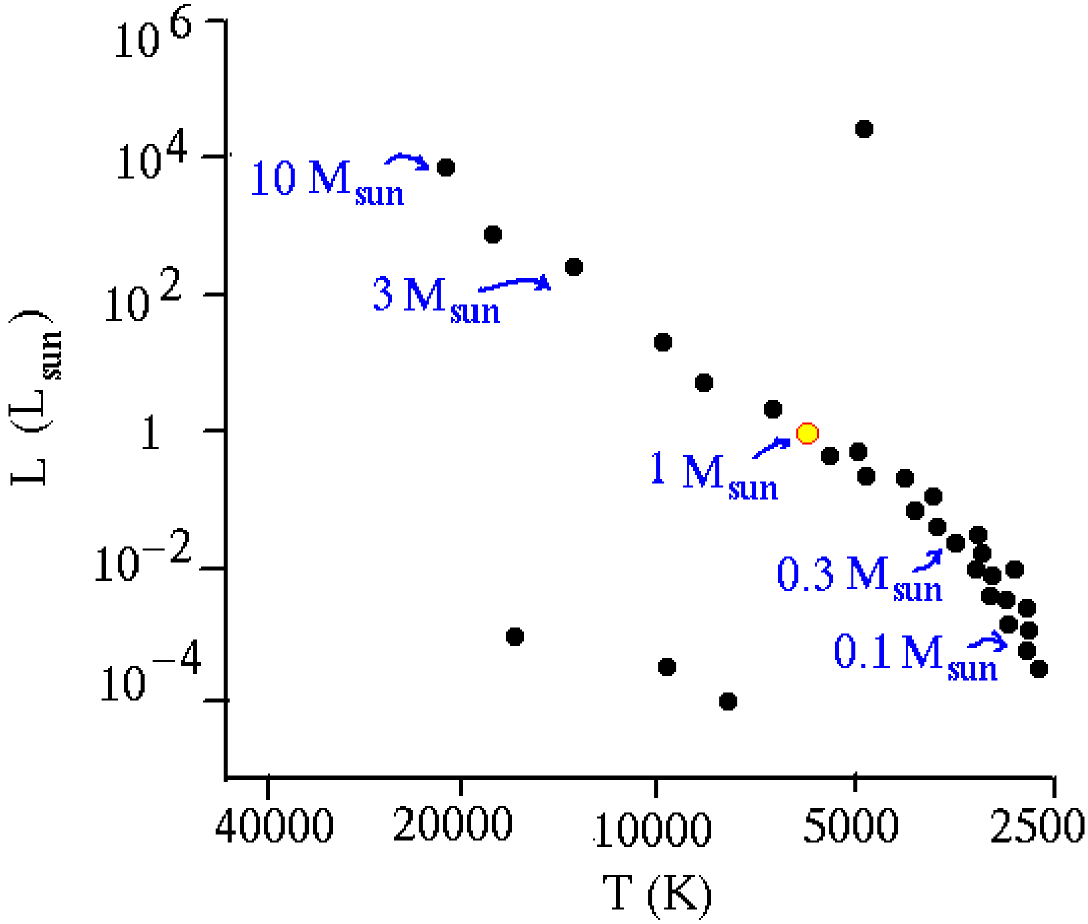




- temperatures must be very high ($\sim$ 10 million degrees), since the particles repel each other electrically

- the reaction rates are *very* sensitive to the temperature ($\propto T^4, T^{20}$)

- the energy released is great enough that the Sun can shine for billions of years



- different positions along the Main Sequence correspond to different *masses* of stars, not to different evolutionary status.

- since more massive stars are hotter in their cores, they produce *much* more energy: a 10 $M_{\rm sun}$ star is about 7000 times as luminous as the Sun

- more massive stars have much shorter lifetimes: a 10 $M_{\rm sun}$ star has a lifetime about 1/700th that of the Sun

- this means that high-mass stars are the first to exhaust their fuel and leave the Main Sequence

- if one looks at a cluster of stars which were all formed at the same time, the high-mass stars will have already evolved off the Main Sequence

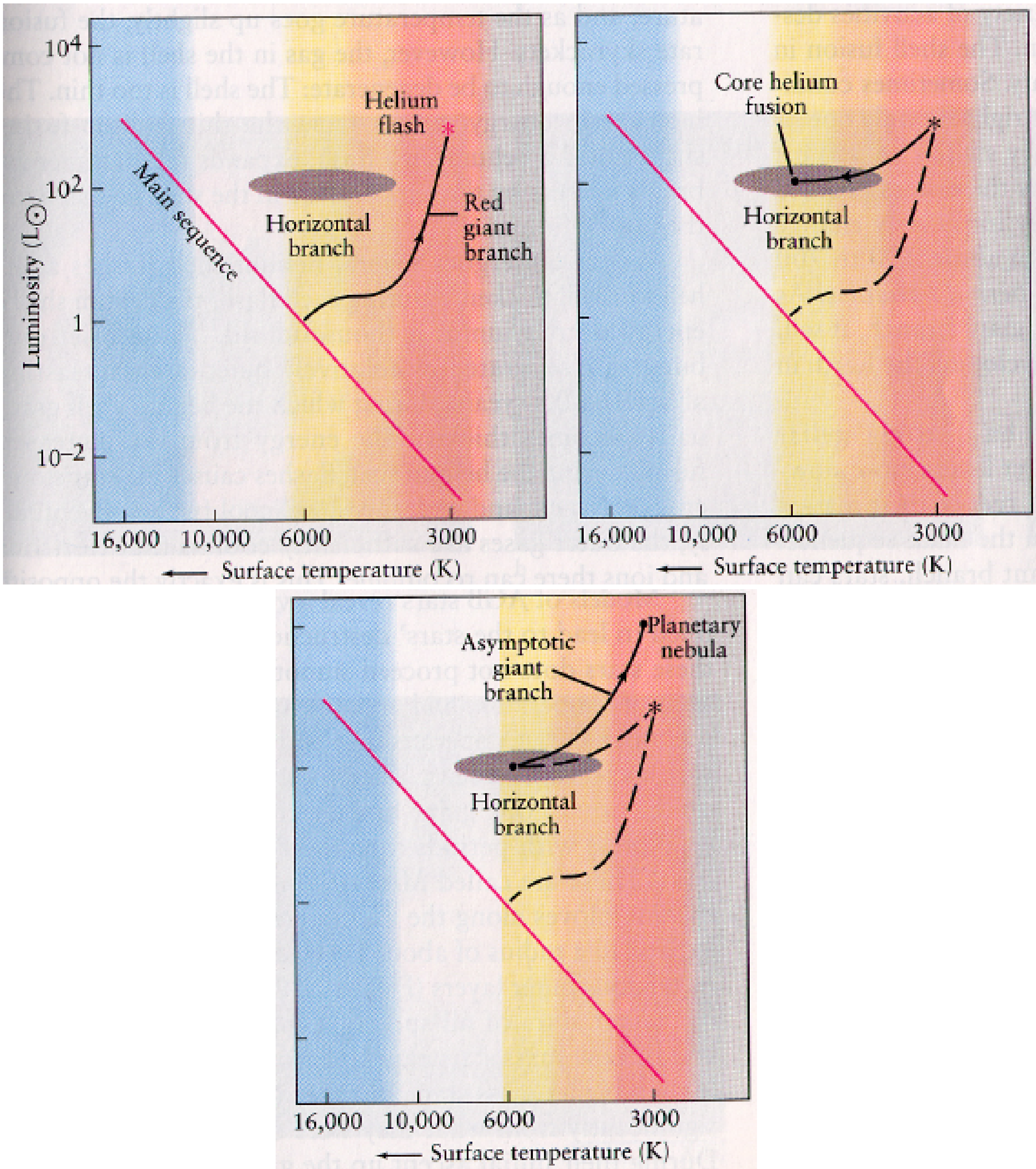
- this can be used to date the age of the cluster . . .

Clusters a very useful because the stars in them are:

- coeval (formed at nearly the same time)
- the same distance from us
- formed from the same composition of material

This makes it easier to use evolutionary models for them to determine the age of the cluster and the stars in it

Evolution of a Sun-like star off the Main Sequence



Why do stars evolve off of the Main-Sequence?

- depleted hydrogen in the core
- core shrinks, becomes hotter (but not yet hot enough to fuse helium)
- the hot core causes the outer layers to puff outward
  - radius increases
  - surface temperature decreases
  - hydrogen fusion now occurs in a shell surrounding the helium core

$\longrightarrow$ the star has become a "red giant"

The core continues to contract and get hotter until the central temperature reaches $\sim$ 100 million degrees

- fusion of helium then begins via the "triple-alpha process"

$$\mathrm{He} + \mathrm{He} + \mathrm{He} \rightarrow \mathrm{C}$$

This continues until all the helium in the core is exhausted.

Now there is a branching depending upon whether the star is low-mass or high-mass:

- for low-mass stars, their core temperatures never rise high enough to fuse Carbon into heavier elements ($\sim$ 600 million K needed)

- for high-mass stars, their core temperatures rise high enough to burn many different elements:

element	temperature	burning time
C	600 million K	600 years
Ne	1.2 billion K	1 year
O	1.5 billion K	6 months
Si	2.7 billion K	1 day

Stars heavier than $\sim 8\ M_\odot$ get to the point of trying to fuse iron (Fe) in their cores

Unfortunately (?), Fe fusion *absorbs* energy rather releases it

$\longrightarrow$ no energy support in core

$\longrightarrow$ core collapses in less than 1 second
... and then bounces and explodes as a supernova!

Such a supernova explosion often leaves behind a remnant:

- a black hole
- a neutron star

Black holes in isolation are virtually undetectable

Neutron stars would be as well, except some of them emit pulses ("pulsars")