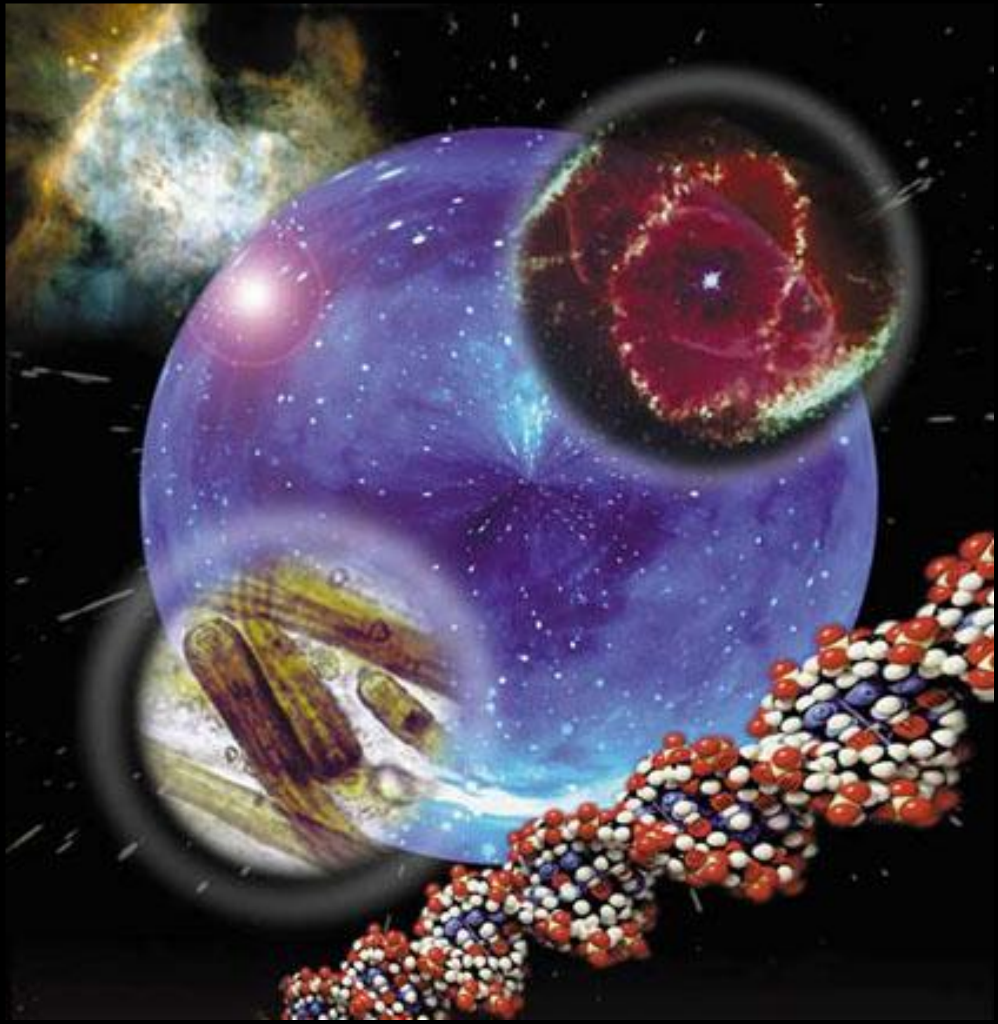
Today in Astronomy 106: life, its components, and the Drake equation

- ❑ Definition of life, and its components.
- ❑ The Drake equation: an accounting measure that suggests a path of inquiry into the emergence of life.
- ❑ Atoms and nuclei
- ❑ Measurement of chemical abundances in stars and nebulae



(JPL/NASA)

The result after 13.7 billion years: life as we know it.

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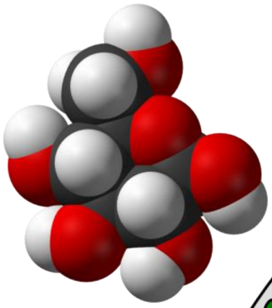

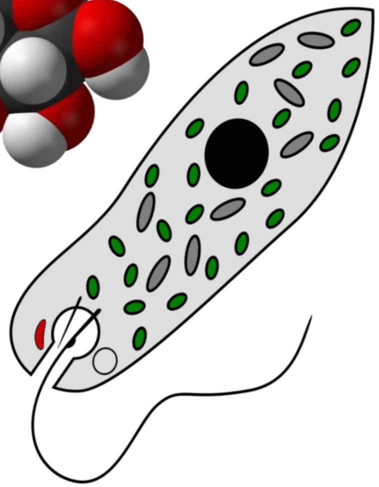

Most things that are alive …

- … are composed of **organic molecules**, based upon long chains and rings of carbon atoms, and **water**.
- …engage in **metabolism,** thus requiring supplies of chemicals and chemical energy.
- … **reproduce.**
- … **mutate:** they adapt and evolve.
- … exhibit **sensitivity**: they respond to changes in their environment.

Chemical composition of Life as we know it

More about the organic molecules and water aspect: much of Life as we know it is similarly composed.

By atom, per hundred oxygen atoms,

Element	Bacteria	Human
Hydrogen	217.2	234.6
Carbon	22.1	40.4
Nitrogen	4.8	9.2
Oxygen	100.0	100.0
Phosphorus	0.4	0.5
Sulfur	0.2	0.5
Calcium	< 0.2	0.9

i.e. CHONSP, as one may have learned in high-school biology.

Chemical composition of Life as we know it (continued)

But this is different from Earth's composition…

Element	Interior	Crust	Ocean	Air	Human
Hydrogen		4.8	200.1	0.002	232.0
Carbon	< 0.1	0.1	0.004	0.1	37.9
Nitrogen		0.0		372.1	5.8
Oxygen	100.0	100.0	100.0	100.0	100.0
Sodium		4.2	0.9		0.2
Magnesium	30.4	3.0	0.1		0.1
Aluminum	2.8	10.3			
Silicon	28.6	33.9			
Phosphorus		0.1			0.8
Sulfur	4.8	0.1	0.1		0.2
Chlorine		0.0	1.0		0.1
Argon				2.2	
Potassium		2.3			0.3
Calcium	2.0	3.1			0.9
Iron	30.6	3.1			
Nickel	1.6				

(by atom, per 100 oxygen atoms)

Chemical composition of Life as we know it (continued)

… and in fact closer to the solar system at large.

Element	Earth's Interior	Sun	Comets	Human
Hydrogen		147058.8	200	232.0
Carbon	< 0.1	44.1	44.1	37.9
Nitrogen		13.4	13.4	5.8
Oxygen	100.0	100.0	100.0	100.0
Sodium		0.3	0.3	0.2
Magnesium	30.4	4.3	4.3	0.1
Aluminum	2.8	0.3	0.3	
Silicon	28.6	3.7	3.7	
Phosphorus		0.03		0.8
Sulfur	4.8	1.4	1.4	0.2
Potassium		0.02		0.3
Calcium	2.0	0.3	0.3	0.9
Iron	30.6	1.2	1.2	
Nickel	1.6	0.2	0.2	

(by atom, per 100 oxygen atoms)

The result after 13.7 billion years: life as we know it.

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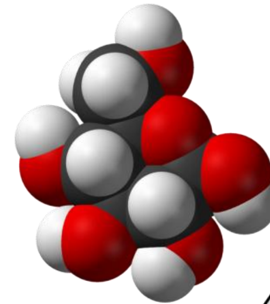

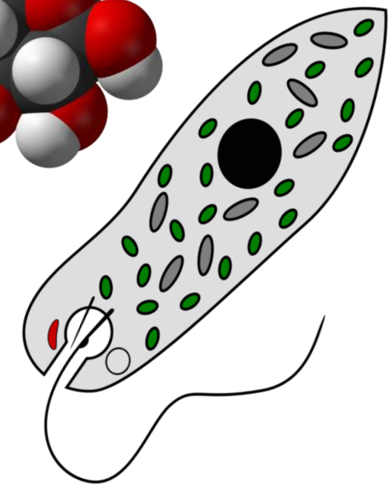

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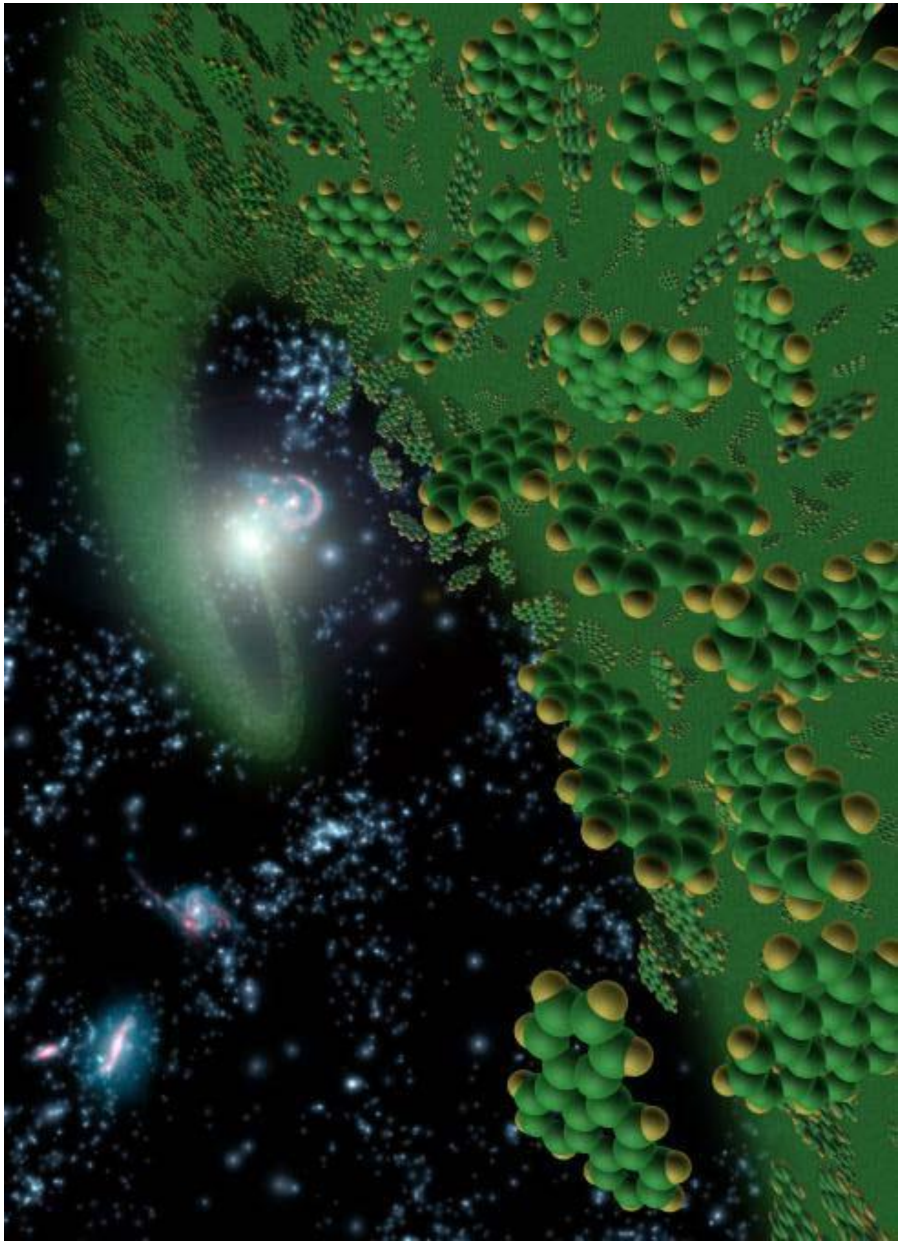


I said *most*…

Are some of these five attributes more exclusively characteristic of life than others?

- ❑ What are some living things that lack one or more of these traits?
- ❑ What are some non-living things that possess one or more of these traits?

Some counterexamples to think about

- Mules are undoubtedly alive, but do not reproduce.
- Viruses are considered by most to be a life form, but they do not metabolize or exhibit sensitivity.
- Robots are not considered alive, but: we can endow them with sensors; program them to build other robots (reproduce) or change themselves or others (mutate, adapt). They require energy and materials to keep going (metabolism).
  - If we started making them out of organic materials, would we call them living?

Are there better ways to define Life?

Many have tried to come up with more general definitions that have fewer exceptions. Notable is Folsome (1979, quoting Onsager and Morowitz), who focused on life as an ecological process:

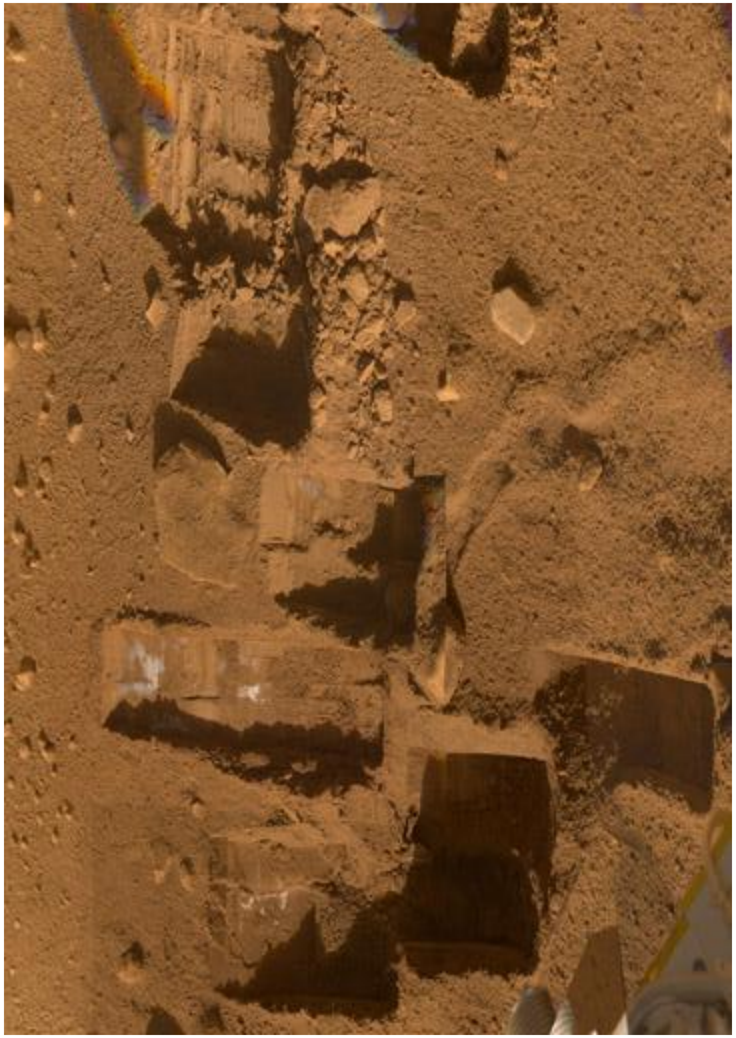
> Life is that property of matter that results in the coupled cycling of bioelements in aqueous [watery] solution, ultimately driven by radiant energy to attain maximum complexity.

Biosphere 2

Are there better ways to define Life? (continued)

And Feinberg and Shapiro (1980):

> Life is fundamentally an *activity* of the biosphere. A biosphere is a highly ordered system of matter and energy characterized by complex cycles that maintain or gradually increase the order of the system through an exchange of energy with its environment.



Digging for ice on Mars (*Phoenix*/U. Ariz.)

Are there better ways to define Life? (continued)

And The Chords (1954):

Hey nonny ding dong,
alang alang alang
Boom ba-doh, ba-doo
ba-doodle-ay
Oh, life could be a dream,
sh-boom.

The more general the definition, the more cryptic life tends to look. Let’s keep all these definitions in mind as we study life’s emergence.

The emergence of life and intelligence: Drake's Equation

So how did life and its components come into existence, during the billions of years of the past?

During the rest of the semester, we will be guided by the equation formulated in the 1960s by Frank Drake as an accounting measure for the universal factors important in the emergence of life and civilization in the Universe.

- Drake phrased the expression in terms of the number of civilizations with which we could eventually communicate, but each **factor** in the equation is related to the development of an important component of life as we have tentatively defined it.
- Also of importance but not a term in the equation: *r*, the average distance to the nearest civilization.

The Drake equation

$$\boxed{N = R_* f_p n_e f_\ell f_i f_c L}$$

N = number of communicable civilizations in our Galaxy

R_* = rate at which stars form.

f_p = fraction of stars that have planetary systems.

n_e = number of planets, per planetary system, that are suitable for life.

f_ℓ = fraction of planets suitable for life, on which life actually arises.

f_i = fraction of life-bearing planets on which intelligence develops.

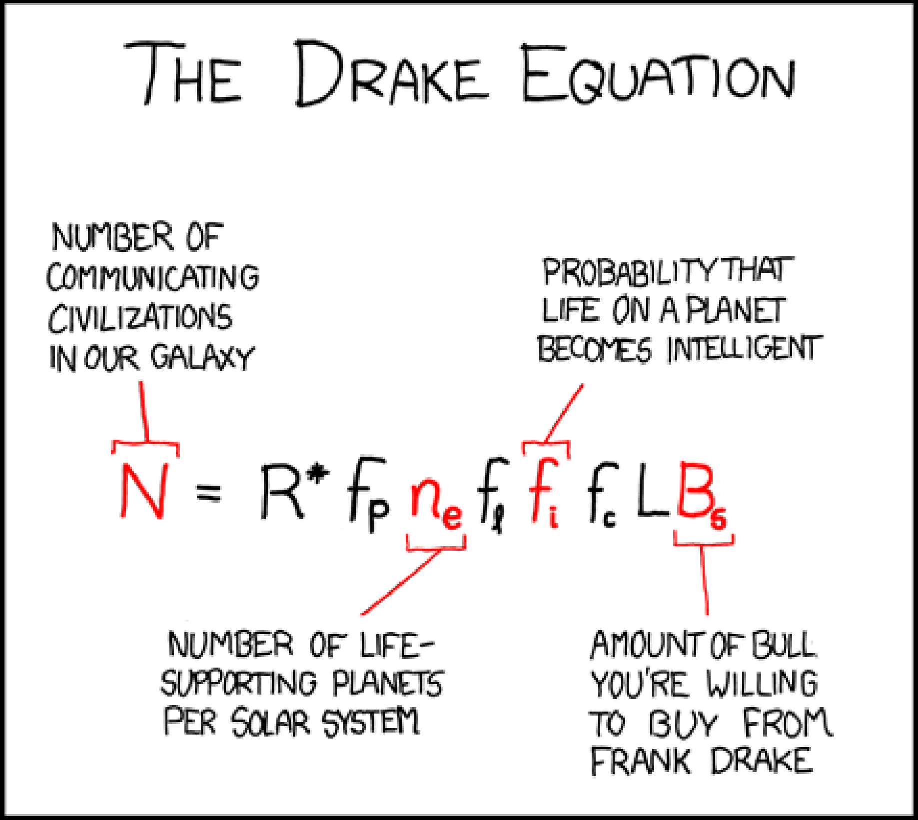
f_c = fraction of intelligence-bearing planets which develop a technological phase during which there is a capacity for, and interest in, interstellar communication.

L = average lifetime of communicable civilizations.

See also Evans, appendix 5.

Mid-lecture Break

- **Homework problem set #1** is on WeBWorK; it's due next Wednesday at midnight.
- Recitations start next week. They are held Tuesday at 12:30pm in B & L 315



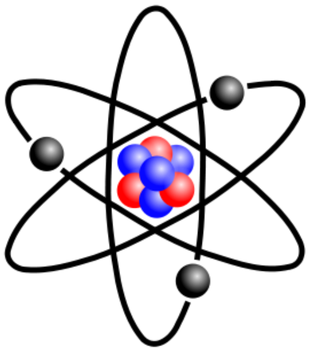
But seriously, there's loads of intelligent life. It's just not screaming constantly in all directions on the handful of frequencies we search. (XKCD)

The parts of atoms

- Electrons, the lightweight ingredients of outer shells.
  Mass: $m_e = 9.1093897 \times 10^{-28}$ gm
  Electric charge: $q_e = -4.803206 \times 10^{-10}$ esu

- Protons, the charged nuclear particle
  Mass: $m_p = 1.6726231 \times 10^{-24}$ gm $\cong 1836 m_e$
  Electric charge: $q_p = 4.803206 \times 10^{-10}$ esu $= -q_e$

- Neutrons, the neutral nuclear particle
  Mass: $m_n = 1.674929 \times 10^{-24}$ gm, 0.14% larger than m_p
  Electric charge: 0 (thus immune to electricity)



^{6}Li atom, not drawn to scale or anything like realistically.

(Wikimedia Commons)

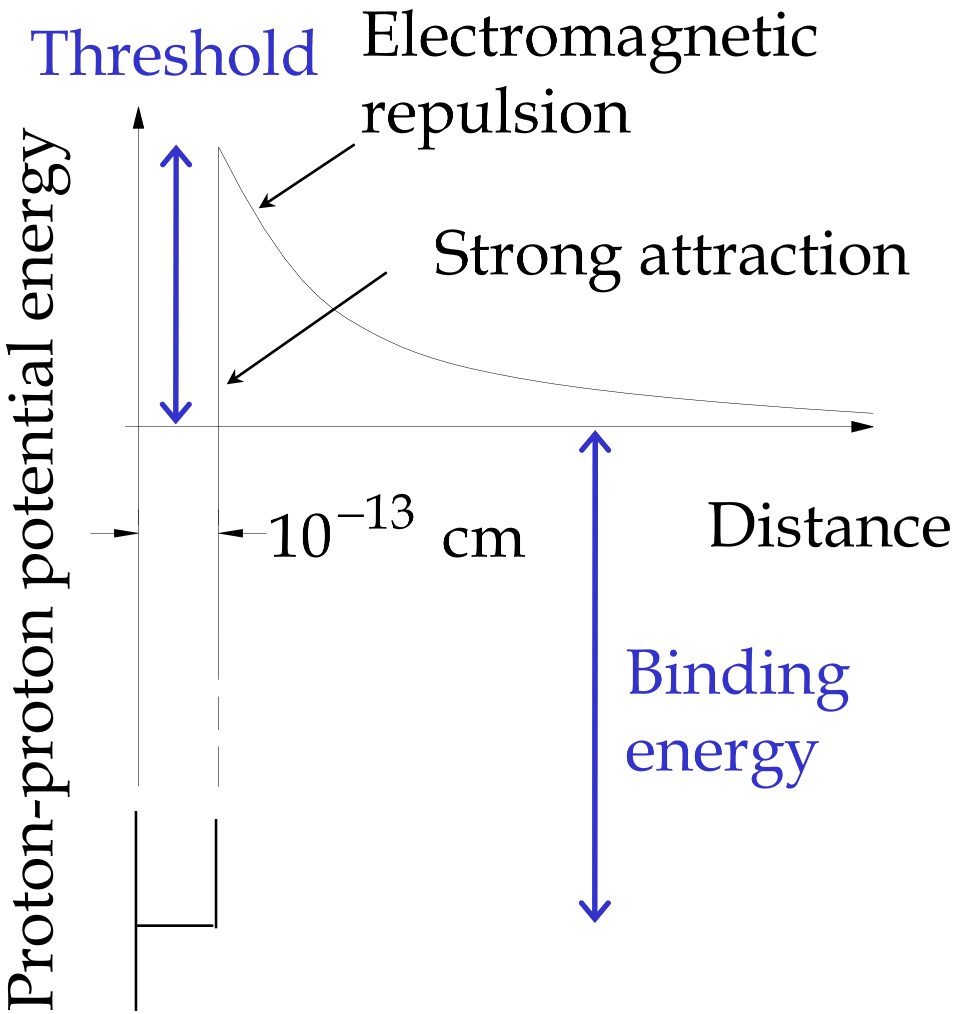
The forces that hold atoms together

- Electrons and nuclei are held together by the **electrostatic force**, typically about 10^{-8} cm apart.
  - Protons in the nucleus and electrons are oppositely charged, and attract each other.
- Protons and neutrons are held together in nuclei by the **strong nuclear force**.
  - This force, always attractive, is much stronger than the electrostatic force, but is short ranged: it doesn't act between objects much further apart than the effective radius of the proton, 10^{-13} cm.
  - Neutrons and protons are identical from the viewpoint of the strong nuclear force.

The force that holds nuclei together

Outside the range of the strong force, protons repel each other, but once within range they stick. Thus there is a **threshold** which must be overcome to stick two protons together that start off far apart.

- Threshold very large: in temperature units, $> 10^9$ K.

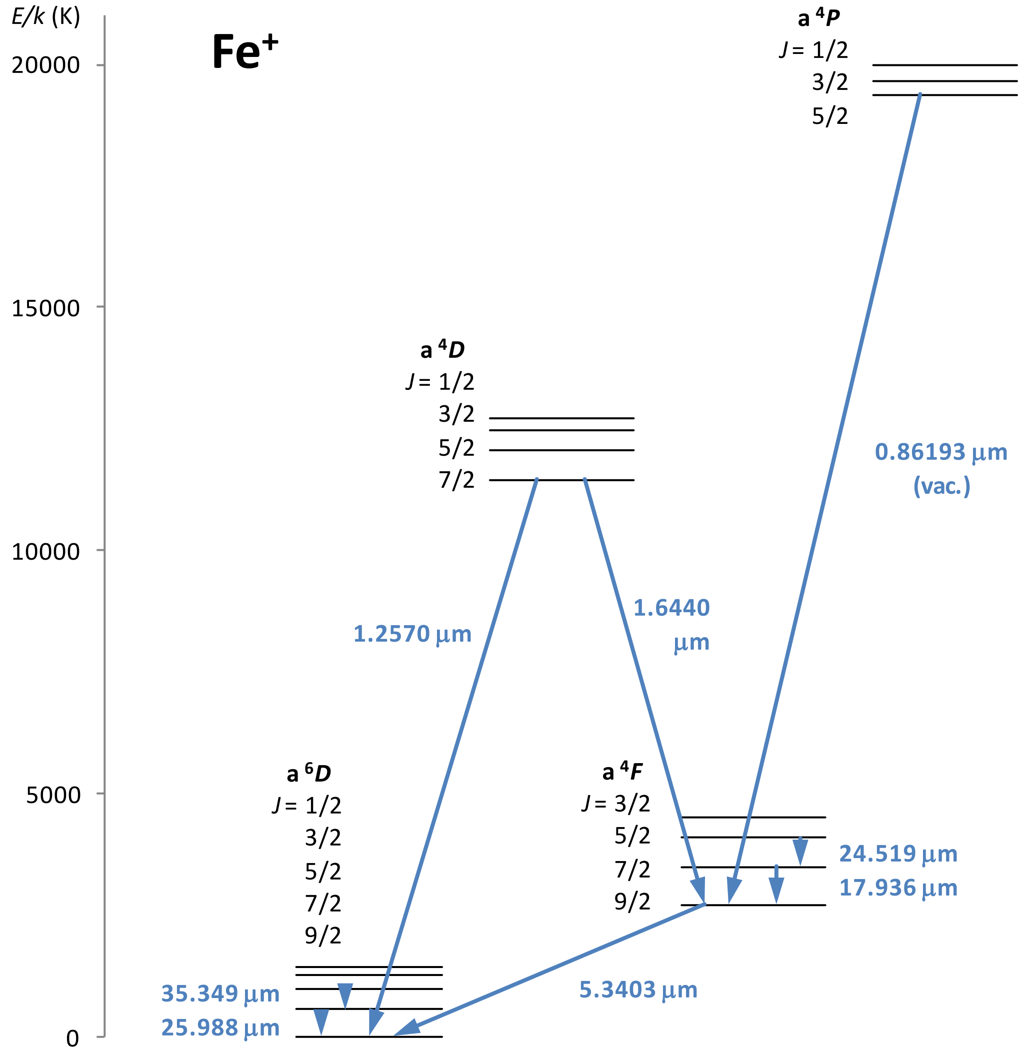


Quantum behavior of subatomic particles

- On the distance scale of atoms (about 10^{-8} cm), electrons **behave as waves** instead of particles.
  - Probability-density waves, to be precise.
  - Waves can **interfere** with one another, constructively or destructively. (Particles can't.)
  - As a result, electrons in atoms can't have any energy they want: only certain energies are allowed. This is called energy-level quantization.
  - Also as a result: if an atomic electron changes from one energy level to another, it either absorbs a particle of light (a **photon**) to do so, or emits one, depending upon whether it's changing up or down in energy.

Example atomic energy levels

Here, for example, are the sixteen lowest-energy states of Fe^+ (singly-ionized iron), showing some of the transitions that are most productive of light emission, and the wavelengths at which Fe^+ emits light when moving down the energy ladder.



Example atomic emission spectrum

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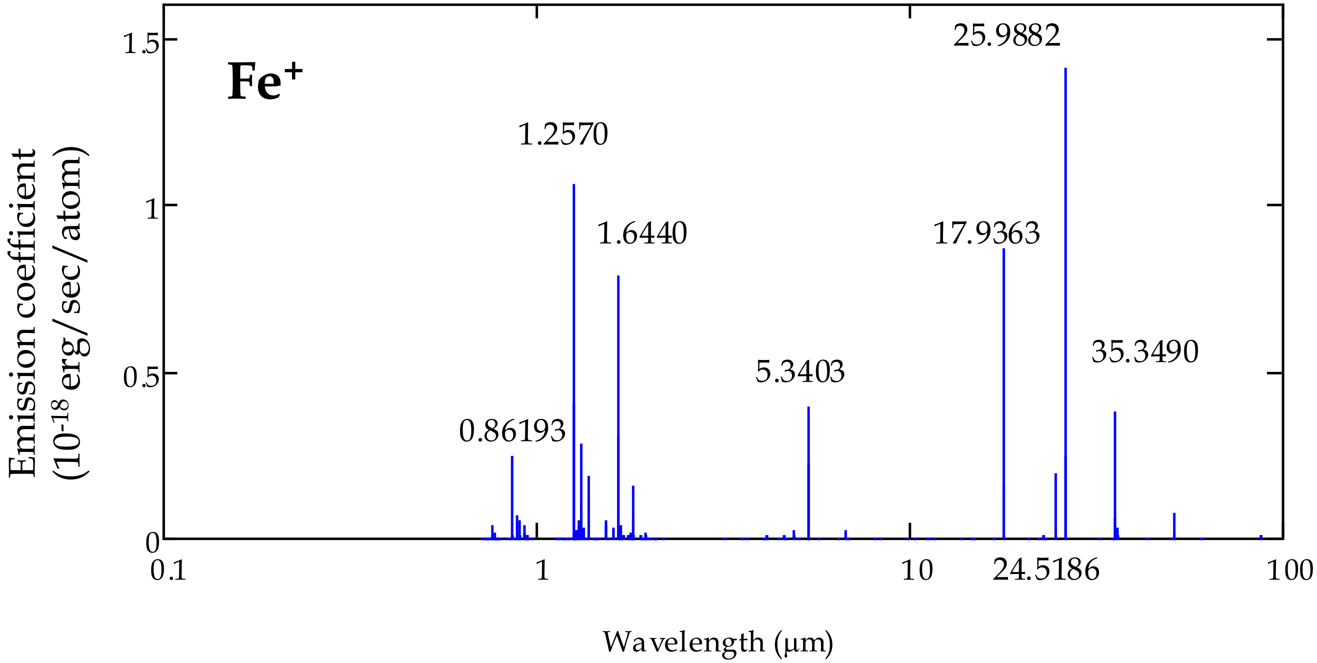
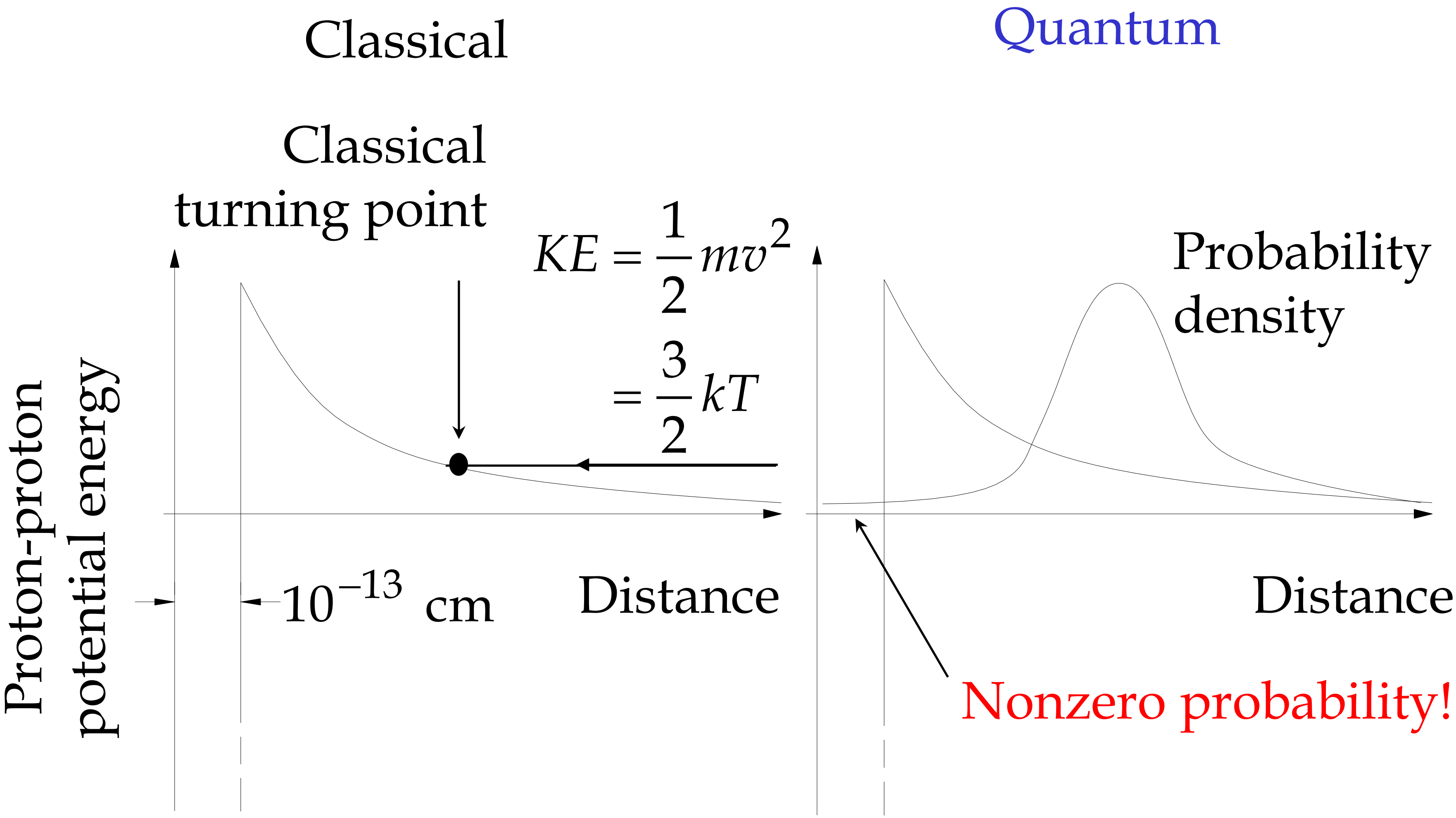
Fe^+ can only emit, or absorb, light at these specific wavelengths. This is called a **line spectrum**, in contrast to the continuous spectrum emitted, for instance, by an incandescent light bulb.



Quantum behavior of subatomic particles (continued)

- On the distance scale of the strong force's range (about 10^{-8} cm), protons and neutrons **behave as waves** instead of particles.
  - Again: probability-density waves, to be precise.
  - Waves extend over **finite** ranges of space. (Particles don't; they're infinitesimally small.)
  - As a result, protons and neutrons can come together and stick even when their kinetic energies aren't quite enough to exceed the threshold. This is called **tunneling** or quantum mechanical tunneling.
  - Tunneling reduces the temperature required for fusion slightly; very high temperatures still required (10^7 K).

Fusion by tunneling



Nuclear upshot: heavier elements can be made by fusion of lighter ones

- Needs **high density** ***and*** **temperature** if lots of the products are desired.
- Some combinations, e.g. He^{+2} (the alpha particle), are peculiarly robust and stable.
- Because the strong force has range smaller than nuclei and the electrostatic force does not, the binding energy per nuclear particle reaches a peak at a certain nuclear size, and thereafter decreases with increasing nuclear size.
  - Peak at ^{56}Fe, the normal isotope of iron.
- So **fusion** which produces elements lighter than ^{56}Fe releases heat, and **fission** of elements heavier than ^{56}Fe produces heat. This makes stars, and nuclear reactors, possible.

Nuclear upshot: heavier elements can be made by fusion of lighter ones (continued)

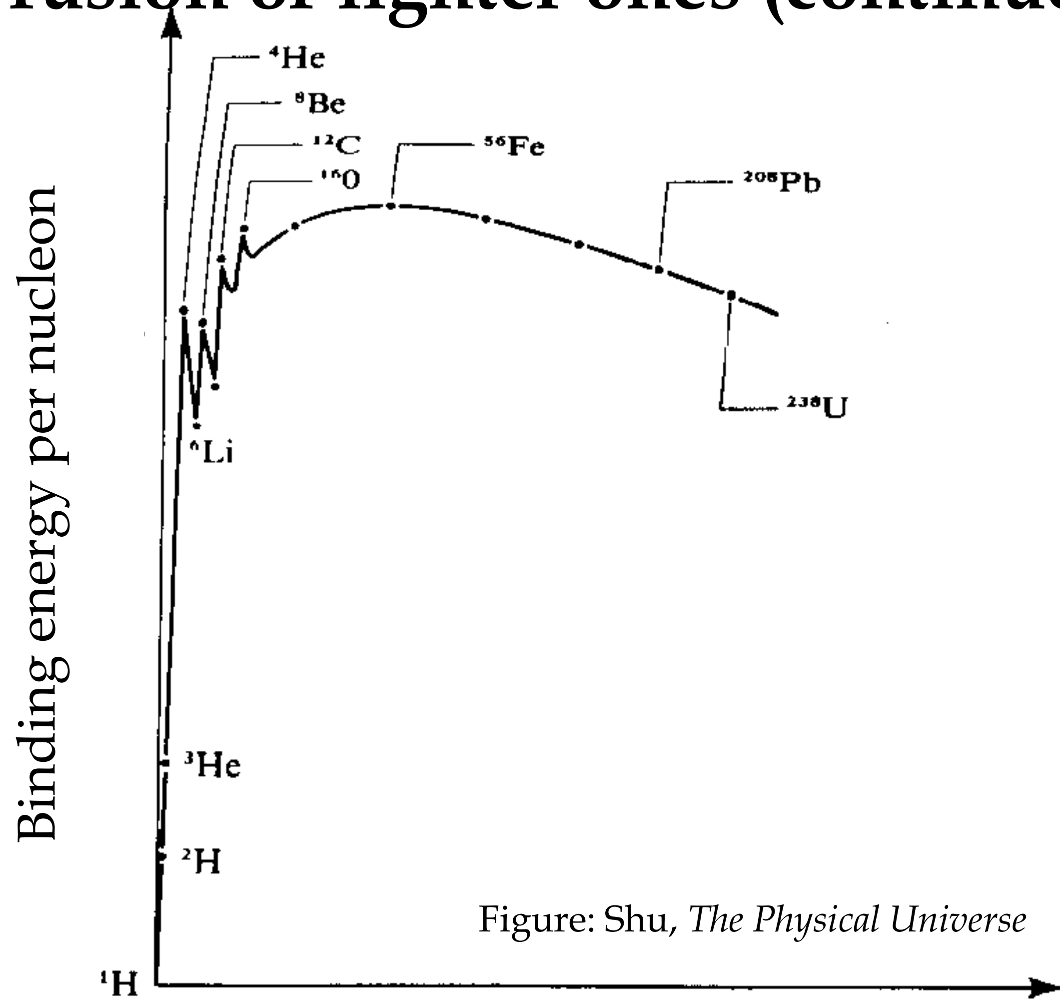


Figure: Shu, *The Physical Universe*

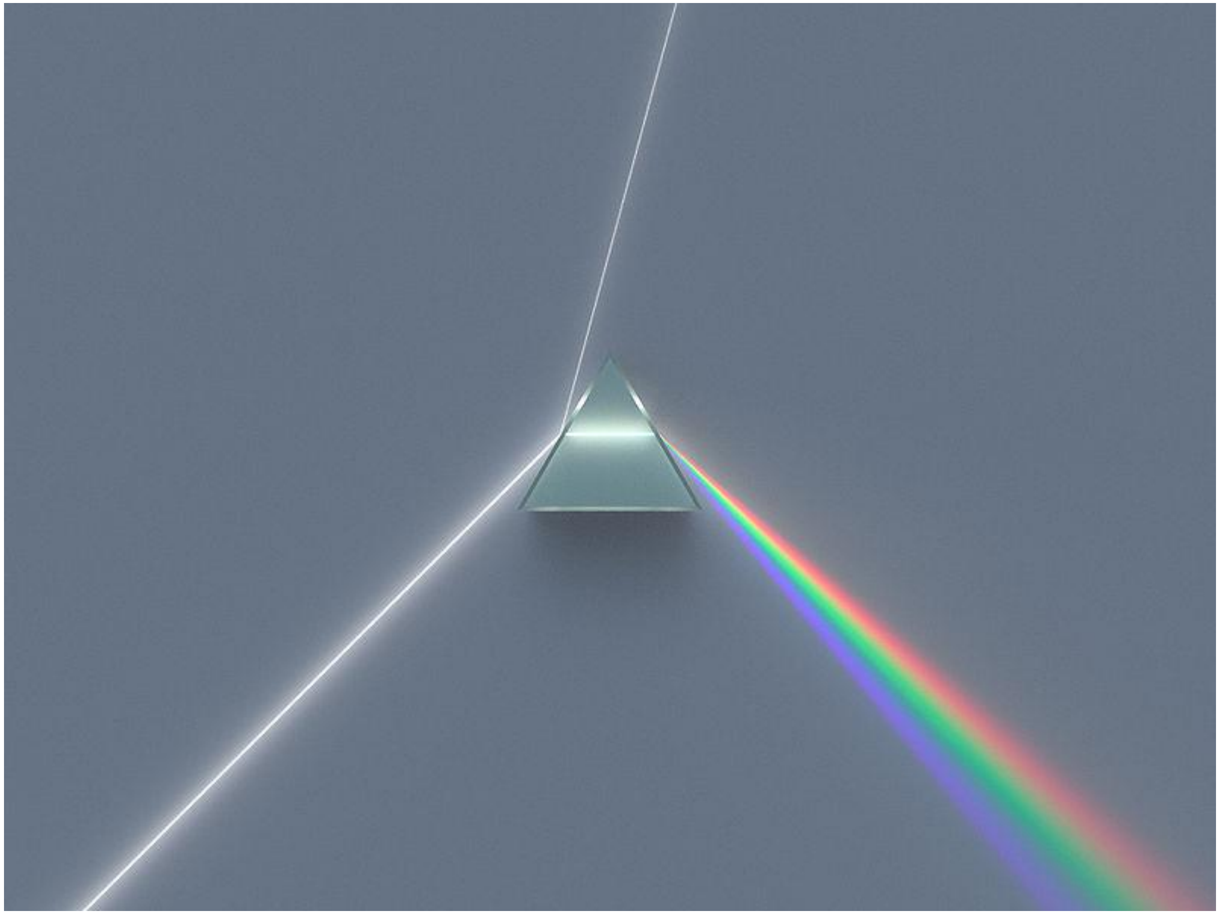
Atomic mass number A (protons plus neutrons)

Atomic upshot: we can measure the relative abundances of the elements in celestial objects

- Every element and isotope has a distinctive set of energy levels, and thus a distinctive spectrum: thus elements and their ions can be identified positively.
- The wavelengths and strengths of the spectral lines can be measured in the laboratory, usually to very high precision and accuracy.
- The relative brightness of lines of a given species can be used to determine density, temperature, and pressure of the emitting region.
- Thus the relative brightness of lines of different species can be used to determine relative abundances. This works for stars and lots of different kinds of interstellar nebulae.

How to measure element abundances, from a great distance

Collect light from the object, using a telescope, and disperse the light into the spectrum, using instruments such as prisms and diffraction gratings.



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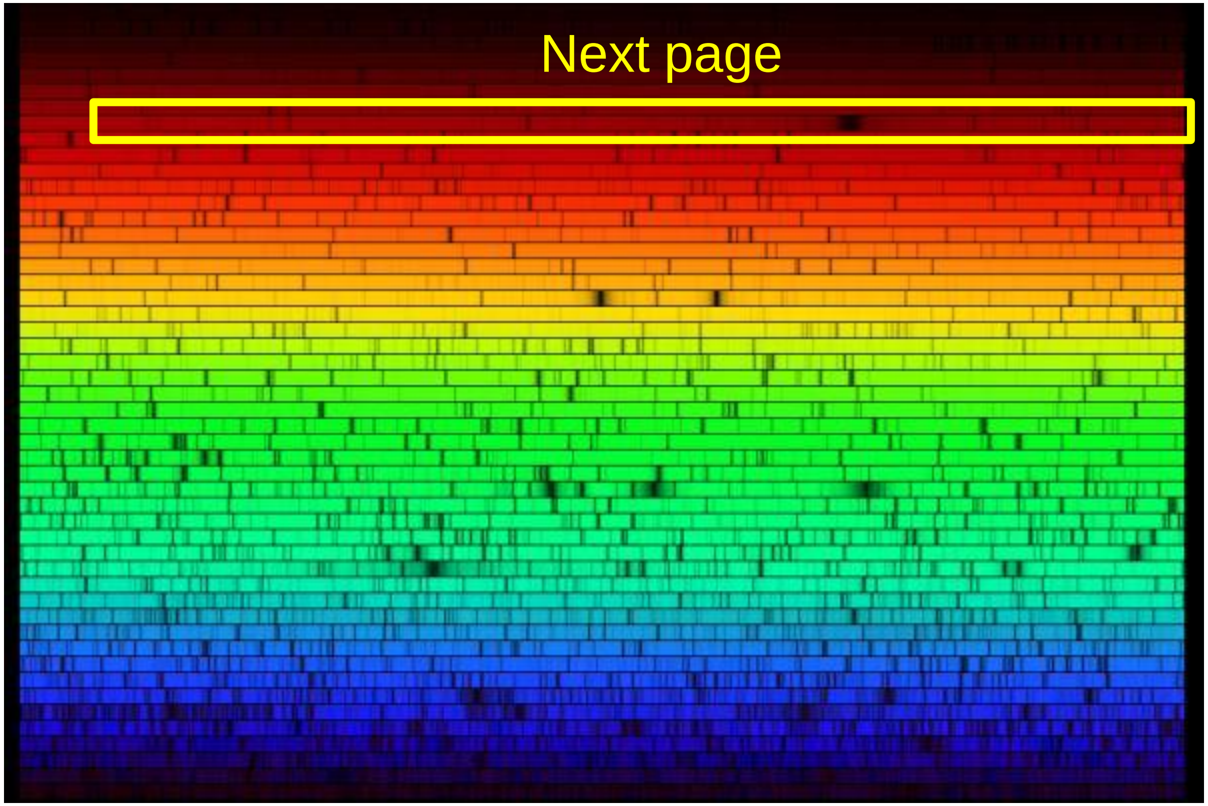
How to measure element abundances, from a great distance (continued)

In stars, this reveals atomic absorption in the star's atmosphere of light generated from the hotter interior.



Cross-dispersed spectrum of the Sun (R. Kurucz and NOAO).

How to measure element abundances, from a great distance (continued)

From the strength of the absorptions relative to one another, the abundances (ratio of numbers of atoms in the object) of elements can be determined. In this short piece of the Solar spectrum, several atomic abundances can be measured.
(R. Kurucz and NOAO)