Nature's Design

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April 20 2004, Designing Matter, #13

Designing Matter Lecture Series:

Topics 1 - 12 span: atoms → humans → earth's surface
Topic 13 (this one): the rest of the Universe…….

In terms of <u>size</u> :

Topics 1-12

Topic 13

Atomic nucleus

Outline

1) Design in Nature: the stage, actors and play.
2) Quick tour: from nuclei to distant galaxies.
3) Universe as a laboratory of extremes:
   size/mass/time/power/density/temperature.
4) Constituents, and their construction/creation:
   nuclei & atoms, particles, matter,forces.
5) Emergence of structure:
   stars, galaxies, clusters/voids.
6) Origin of energy.

Shakespeare : “As You Like It”

Reflections on human life

“All the world’s a stage,
And all the men and women merely players.
They have their exits and their entrances,
And one man in his time plays many parts,
His acts being in seven ages.”

Deep Contents

- Space & Time (space-time)
- Matter (particles)
- Forces (act between particles)

  4(5) : strong, electromagnetic, weak, gravity, (QM)

- Rules (quantum/classical physics)

  (e.g. conservation laws, QED, QCD, GR)

Together, these make four basic structures

Four Basic Structures

	FORCES
• Nuclei	strong, **EM, QM**
• Atoms	**EM, QM**
• Stars/Planets	gravity, **EM, QM**
• Galaxies	gravity

Lets begin our brief tour of these basic structures

Atoms:

Nuclei:

protons

neutrons

Electrons

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 Y	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

MORE QUERY METHODS | NEW RELEASES

Solar magnetic surface storm

© Anglo-Australian Observatory

Full dark sky (Milky Way dominates)

North & South Hemispheres

Nous sommes
ici

NGC 891 edge on Spiral Galaxy

© Anglo-Australian Observatory

Two young star clusters

NGC 3603
Hubble Space Telescope • WFPC2

Slow death of low mass star

Explosive death of high mass star

Supernova remnants:

Recycles material back into the ISM where it is incorporated into the next generation of stars.

Keyhole Nebula

Hubble Heritage

NASA and The Hubble Heritage Team (STScI) • Hubble Space Telescope WFPC2 • STScI-PRC00-06

New star-formation region

New stars in Orion

Early stage of star/planet formation

Our Galaxy

Earth	=	100 nm	=	virus
Sun	=	10 µm	=	cell
Earth orbit	=	¼ cm	=	pin head
Solar system	=	20 cm	=	saucer
Nearest star	=	250 m	=	lawn

NGC 221
E2
Maffei I
E3
ESO 28610
Sa
NGC 6942
SBa
NGC 4138
S0
NGC 4111
S0 (edgeon)
NGC 5985
Sb
NGC 5850
SBb
NGC 4553
S0/Sa
NGC 2983
SB0/SBa
NGC 5457
Sc
NGC 7479
SBc

Sombrero Galaxy • M104

Hubble Heritage

NGC 3310
Spiral Galaxy

NGC 5194
Spiral Galaxy

NGC 1365
Barred Spiral Galaxy

Interacting galaxies

Hibbard & van Gorkom 1996, AJ, 111, 655

Merging galaxies N-body simulation

NGC 6240 post merger galaxy

Merging group of galaxies

NGC 4686
Giant Elliptical Galaxy

A 1689
Rich galaxy cluster
2 Gly distant
Gravitational lens

1 million galaxies

(stars removed, ~120 degrees of sky)

SDSS : ⅓ million galaxies

HDF
Alkaid
Mizar
Alioth
URSA MAJOR
Dubhe
Phecda
Mirak
Tania Austrailis

Hubble Deep Field
~1500 galaxies
Sky area ~2.5×2.5 arcmin
≡ pinhead @ arms-length

Age of the Universe

Today: 14 Billion Years | 9 Billion Years | 5 Billion Years | 2 Billion Years

Elliptical

Spiral

Galaxies: Snapshots in Time

HST • WFPC2

SPACE TELESCOPE SCIENCE INSTITUTE

PR94-52c • Office of Public Outreach • December 6, 1994 • ZGL

Galaxy Building Blocks

Hubble Space Telescope • Wide Field Planetary Camera 2

PRC96-29b • ST ScI OPO • September 4, 1996 • R. Windhorst (Arizona State University) and NASA

The Visible Universe

3. Universe as a creative laboratory

The Universe is a wild and wonderful place !

- it is vast, beyond imagination
- its building blocks are minute, beyond imagination
- Almost all of it is:
  - hotter or colder
  - denser or more rarified
  - more powerful or more delicate
  - evolves faster or more slowly

} than we can possibly imagine

Within such extremes, the Universe is highly creative

Lets try to locate our world amongst these properties, and identify where creativity arises, and why…….

Human World
mm
cm
km
100 km
neutron star material
room of rock
room of water
sequoia
whale
cars
Mountain
white dwarf material
room of air
Horizon
water density
People
breakfast cereal
dust speck
sand grains
Insects
interstellar medium
1 kton
1 ton
1 gm
1 mg
Mass (kg)
Size (meter)
10^6
10^4
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-4}
10^{-2}
1
10^2
10^4

Nature's building blocks
nm
μm
AU
pc
Mpc
Visible Universe
Stars & Planets
Galaxies
Human World
Nuclei
Atoms
Mass (kg)
Size (meter)
10^{60}
10^{50}
10^{40}
10^{30}
10^{20}
10^{10}
1
10^{-10}
10^{-20}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
10^{30}
10^{30}
10^{20}
10^{10}
1
$M_{\odot}$

Matter in the Universe
nm
µm
AU
pc
Mpc
Black Holes
Universe
voids
clusters
galaxies
ISM clouds
SMBH
W.D
B.H.
Sun
S.S.
N.S.
Jup.
Earth
mountain
human
H.W.
cell
U nuc
H nuc
U atom
H atom
Mass affects spacetime
Nuclear density
Atomic density
Closure density
(5 H atom m-3)
Mass (kg)
Size (meter)
M☺

Complexity in the Universe

Energy and Time in the Universe
fs
ns
ms
min
d
y
ky
Gy
A_U
10^{60}
10^{40}
10^{20}
1
10^{-20}
Energy (Joules)
QSO
supernova
stars
10 km asteroid impact
tectonics
All
H
Bombs
A
storm
car crash
lunch
human world
wristwatch
"hello"
MW
1Watt
μW
cells
nuclei
γ
X
UV
Vis
IR
photons
atoms
molecules
evolution
MT
1 t TNT
GeV
eV
10^{-20}
10^{-10}
1
10^{10}
10^{20}
Time (seconds)

Location & state of baryonic matter

Composition History of Universe

4. Creation of elements & particles

We must go inside stars and back to the Big bang.

We consider the creation of three things:

1) heavy elements (nuclei) in stars
2) helium in the Big Bang (1-5 mins).
3) protons/electrons in the Big Bang (< 1sec)

Thermonuclear energy core
Radiative zone
Convective zone
0.2
0.4
0.6
0.8

Nuclear Binding Energy Curve

©Brooks/Cole Publishing Company/ITP

Fusion

H + H ⟶ He

Fission

U ⟶ Xe + Sr

Periodic Table of the Elements

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5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Cosmic abundances for all isotopes of all elements (relative to Si = 10^6)
α elements
Iron peak
"rare" earths
"light" elements
Abundance [Si = 10^6]
Mass number A
H
He
Li
B
C
N
O
Ne
Na
Mg
Si
F
P
Ar
Ca
Ti
Fe
Ni
Zn
Ge
Se
Kr
Zr
Sn
Te
Ba
Dy
Yb
Hf
Pt
Au
Hg
Pb

Creation of the α elements

First steps up the element sequence

$4H \rightarrow He^4$ (α particle)

$He^4 \xrightarrow{+\alpha} Be^8 \xrightarrow{+\alpha} C^{12} \rightarrow$

$C^{12} \xrightarrow{+\alpha} O^{16} \xrightarrow{+\alpha} Ne^{20}$

Heavier elements come from High Mass stars

Pre-supernova red supergiant star: onion shell core

Valley of Stability

<u>Not all nuclei are stable</u>

a) Need ~correct ratio of #protons / #neutrons
b) Filled shell of n or p is more stable

The origin of shells & magic numbers in atomic nuclei

As in atoms, nuclear force field creates nucleon energy levels

Significant gaps create "filled shells" similar to noble gases.

Slow & rapid neutron capture → trans iron-peak elements

Full element sequence from s & r process

Abundances with sources

What about helium ??

- He^4 is extremely common: ~25% <u>everywhere</u>
- far too much to come from stars
- even <u>oldest</u> stars have ~24% …..

→ It was made before all stars, in the big bang

- We see the Universe expanding (with $v \propto d$) suggests all together 14Gyr ago

→began with "Big Bang"
High temp & density → lower temp & density

Temperature history of the Universe

time (seconds)
10
10^2
10^3
10^4
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
fraction of total mass
protons
neutrons
He^4
H^2
He^3
H^3
neutrons
Be^7
H^2
Li^7
Li^6
3×10^9
1×10^9
3×10^8
10^8
temperature (kelvins)

What about protons & electrons ??

- were p, n, e^- made at some earlier time ?
- if so, how ?
- what about other particles (μ, υ, q…) ?
- what about anti-matter, was it also created ?

- must consider <u>energy</u> ←→ <u>matter</u> interchange
- must visit much earlier times

well-known physics:	back to ~1 μs	
~known physics	:	back to ~10^{-12} sec
~rough guesses	:	back to ~10^{-35} sec
profound ignorance	:	before ~10^{-43} sec

Energy / Matter Interchange

Matter is very concentrated energy : $E = mc^2$

$1\text{kg} \equiv 10^{17}$ Joules = 100 megatons (big H bomb)

Examples of matter into energy:

In general: particle + anti-particle → energy

$e^- + e^+ \rightarrow 2\gamma$ (½ MeV photons created)

Examples of energy into matter:

In general: energy → particle + anti-particle

$2\gamma \rightarrow p + \bar{p}$ (need >1 GeV γs)

KE can also create matter:

(need KE > $2m_ec^2$

= threshold energy)

Energy / Matter Interchange

Consider extremes of temperature:

temperature = KE / particle ($E_{pcle} = k \times T$)

what happens when E_{pcle} > threshold energy ?

eg: 6×10^9 K (electron); 1.1×10^{13} K (proton)

→ matter/anti-matter created out of thermal energy

→ new matter arises in the midst of existing matter

The First Day

The First 1000 Gyr

The First Nanosecond

5. Origin of cosmic structures

- Today's Universe is extremely lumpy
  - clusters, galaxies, stars, planets, people…..
  - with very very little in between
- But, the Universe started out smooth
- How did the structure arise ?
  - there must be initial variation/ripples
  - which are amplified (by gravity?)
- Observe the early Universe by looking far away

→ the Cosmic Microwave Background (CMB)

The Microwave Background

Gamma Rays
X-Rays
Ultraviolet
Visible
Infrared
Microwaves
Radio, TV
MAP
mw ovens
10 -16
10 -14
10 -12
10 -10
10 -8
10 -6
10 -4
10 -2
(1 cm)
10 0
(1 meter)
10 2
Electromagnetic Wavelength (meters)

CMB is Young and Far

COBE satellite
(1992)

WMAP satellite
(2003)

Wavelength [cm]
10
1
0.1
Brightness L [erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
Penzias & Wilson
3.5±1.0 K
FIRAS COBE satellite
DMR COBE satellite
LBL - Italy White Mtn & South Pole
Princeton ground & balloon
Cyanogen optical
2.728 K blackbody
1
10
100
Frequency [GHz]

COBE DMR Microwave Sky at 53 GHz

0 3.64 K

Model evolution of this region
Gravity amplifies density contrasts

Computer Simulation
1 Gly region
~10^7 galaxies form
13 Gyr = 2s

SDSS : ⅓ million galaxies

Computer Simulation
10 Mly region
~10^3 galaxies form
13 Gyr = 20s

Sound waves :
red/blue = high/low
gas & light pressure

Many waves of
different sizes,
Directions & phases,
all "superposed"

Water waves :
high/low level of
water surface

Generating cosmic sound

a) gas falls into valleys to make first compression

b) it then rebounds out to make first rarefaction

c) then back in again to make second compression

→ the oscillation continues → sound wave created

Nature of Cosmic Sound

1. Volume :

pressure variations ~ 1/100,000
corresponds to about 90 dB
→ Loud but not cacophonous

2. Pitch :

measured wavelengths 20,000 – 200,000 lyr
pitch 10^{-12} – 10^{-13} Hz (v ~ 0.6c)
→ 48 – 52 octaves below concert A (440 Hz)

3. Quality :

need to construct the "power spectrum"

Maps Power Spectra

Lineweaver 1997

Low frequency

High frequency

harmonics

Low pitch
Long wavelength

High pitch
Short wavelength

Properties from the CMB

• Age of Universe	13.7 Byr	(2%)
• Flatness	1.02	(2%)
• Atoms	4.4%	(9%)
• Dark matter	23%	(15%)
• Dark energy	73%	(5%)
• Hubble constant (km/s/Mpc)	71	(6%)
• Photon/proton ratio	1.6×10^9	(5%)
• Time of first stars	180 Myr	(50%)
• Time of CMB	380,000yr	(2%)

The cosmic concert hall

The universe is **not** a perfect concert hall

There is distortion en-route and local noise.

Similar to carpet+drapes in a concert hall plus a noisy audience adding distractions.

Correct for these problems using detailed computer calculations of the early Universe.

Observed : $C(l)$ → Pure : $P(k)$

Power Spectra : Observed C(l) & True P(k)
Relative Amplitude
1.2
1
0.8
0.6
0.4
0.2
0
0
500
1000
1500
2000
Frequency : angular (l) & linear (k)

Into the fog : yet earlier times

The CMB shows the sound at 380,000 yrs

What was the sound like **before** then ?

We can't see beyond the CMB foggy wall !

But computer models can take us there

Earlier times :

→ Gas only had time to fall into **smaller** "valleys"

→ Wavelengths are shorter, **frequencies higher**

→ Amplitudes lower, sound is **quieter**

Examples :

Evolution of Power Spectra : P(k,t)
Relative Amplitude
Frequency (Hz = 10^4 k)
300,000 yrs (z~1300; ~200 Hz)
65,000 yrs (z~3000; 330 Hz)
5,000 yrs (z~12000; 1150 Hz)
0
0.2
0.4
0.6
0.8
1
1.2
0
500
1000
1500
2000

Growth of Cosmic Sound
Sound pressure
0
0.2
0.4
0.6
0.8
1
Big Bang
Equality
Recombination
Time (kilo-years)
0
100
200
300
0
500
1000
1500
2000
Effective frequency (Hz)
Deep
High

Growth of Cosmic Sound
Sound pressure
0
10⁻⁸
2×10⁻⁸
3×10⁻⁸
4×10⁻⁸
5×10⁻⁸
6×10⁻⁸
Big Bang
Equality
Recombination
Relative Size
0
0.5
1
0.1% current
0
100
200
300
400
500
Wavelength (kilo−lyr)
High
Deep

The first sound : striking the bell

Although gravity amplifies sound, there must be initial irregularities, what caused these ?

Deep mystery, but recent progress :

- → Quantum roughness in early universe
- → Amplified by $\sim 10^{50}$ during inflation at $\sim 10^{-35}$ sec
- → Inaudible quantum hiss made audible by inflation
- → All structure in the universe due to quantum effects !

What did the quantum hiss sound like ?

- → Its power spectrum is **flat** → "white noise"
- → Gravity's amplifier then distorts the sound to make the final power spectrum with its harmonics

Low pitch
Long wavelength

High pitch
Short wavelength

From sound to structure

Gravity amplifies sound into structure, right?

Wrong !! ….. it is too **quiet**

at the CMB, the maximum fluctuations are ~10^{-5} at the 1st peak (size ~2×10^5 lyr), all others are weaker. This is too small to grow quickly into stars & galaxies.

→ We need something else with greater variation ??

Dark matter comes to the rescue

→ it feels no pressure

→ it keeps collapsing from early times (no rebound)

→ At CMB, fluctuations are large (~10^{-2})

→ P.S. shows no harmonics, power at high frequencies

last
Large scale structure
next
galaxies
first
stars
Power Spectra of Baryons and Dark Matter
0-1 Myr
Dark Matter
Baryons (= Atoms)
Z=400
Z=600
Z=800
Z=1000
Log Amplitude
1
0
−1
−2
−3
−4
−5
−6
0
1000
2000
3000
4000
Effective frequency Hz = 10^4 k

Collapse from early gas concentrations to form the first stars

6. Origin of Energy

- In high school we learn:
  - many types of energy (heat/light/KE/chemical,nuclear..)
  - conversion from one type to another is possible
  - such conversions always conserve energy
  - energy can facilitate transformations: eg
    - sunlight drives/creates the biosphere
    - energy needed to purify and fabricate material things

- Where does all this energy ultimately come from ?

Origin of Energy (ii)

- All energy arises when particles "drop" down the potential associated with one of the four forces

- Examples:
  - chemical energy: electrons closer to nucleus
  - nuclear energy: protons/neutrons packed tighter
  - gravitational energy: released when objects fall

- Sometimes need one to enable another

  eg : starlight (sunshine)

  collapsing star (gravity) heats core (particle KE) enabling protons to overcome repulsion and combine, dropping down the (short range) nuclear potential

Origin of Energy (iii)

- Ultimately, then, energy arises because things are initially far apart, and then come closer.

- What separated everything initially ?

  → The Big Bang !!
  → specifically, inflation which drove expansion
  → inflation stored energy in all the force fields
  → to be released later, when circumstances allow

- Without fluctuations, gravity could never have begun the process, energy production would have ceased following He^4 production & recombination

LITE

Lineweaver 1997

Dark Matter

Invisible particles (WIMPS?),
Pervasive: surrounds galaxies,
Dominates mass: 7 x atomic matter