Cosmological Mysteries

Dark Matter and Structure formation in the Universe

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http://astro.uchicago.edu/~andrey/talks/mysteries
Solar System
The Infrared Milky Way  This map of the infrared sky includes the light of a half billion stars

Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts
Galaxy NGC 1512
Hubble Space Telescope • FOC • NICMOS • WFPC2

NASA, ESA, and D. Maoz (Tel-Aviv University and Columbia University) • STScI-FRC01-16
Galaxies come in different shapes and sizes
Einstein's Cosmological Principle:

The Universe, on average, is homogeneous (equal density everywhere if averaged over a sufficiently large volume) and isotropic (it looks the same in all directions).

Is distribution of galaxies in space consistent with this?

Albert Einstein (1878-1955)
The Local Supercluster

Gerard de Vaucouleurs
1918-1995

G. de Vaucouleurs
From 2D to 3D: using expansion of the Universe to map it

Palomar 48-inch Telescope used for Sky Surveys

Edwin Hubble
(1889-1953)

U. Chicago alum!
(PhD, 1917)
Expansion of space

earlier epoch

later epoch
Cosmological Redshift as a measure of distance and time

redshift
Distance
Age of the Universe
Large-scale distribution of galaxies

at distances less than 300 million light years

CfA galaxy survey 1980-1990
The quest for uniformity

REDSHIFT SURVEY by the Harvard-Smithsonian Center for Astrophysics (CfA) in the mid-1980s discovered the first Great Wall but was too limited to apprehend its full extent.
The end of greatness...

Distribution of galaxies on even larger scales

2004, Sloan Digital Sky Survey (SDSS)
Back to the "small" scales: galaxy clusters

Sloan Digital Sky Survey (SDSS)
Perseus cluster:

‘Constellation’ of galaxies
Clusters and Dark Matter

Fritz Zwicky
(1898–1978)
Clusters are filled with hot gas

X-ray emission from the Coma cluster indicates copious amounts of gas at \( \sim 50 \text{ million degrees Kelvin} \).
"Observations" of Dark Matter
(Some of)

The Current Cosmological Mysteries

☐ Is the Universe full of weird dark matter? Or, even weirder, dark energy?

*the answer appears to be YES. how we know? what is Dark Matter? what is Dark Energy*

☐ How did it all begin? How did the structures form?

*understanding how the structures, and galaxies in particular, form is critical to understanding the origins of everything we see around us, including the intelligent life*

☐ How do we find out?

*a variety of new observations, sophisticated computer modeling using modern supercomputers*
Einstein's theory of General Relativity

curvature of space = matter + energy

Content of the Universe:
all existing components (protons, neutrons, hypothetical dark matter) contribute to gravity and can influence the rate with which the Universe expands

The contribution of each component is measured in units of
critical density: \( \Omega_i = \rho / \rho_{\text{crit}} \)

\[ \rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} = 1.8788 \times 10^{-29} h^2 \text{ g cm}^{-3} \]
Content of the Universe: observational probes

☐ Ripples in the Cosmic Microwave Background

physical processes causing tiny fluctuations in the temperature of the relic microwave radiation are well understood. We can predict them much better than the weather!

☐ Large-scale structure of the Universe

galaxies, galaxy clusters, filaments

☐ Standard "candles"

any object whose intrinsic brightness is known or can be deduced from observations without using distance. SNIa are currently the best cosmological standard candles known

☐ Standard rulers (systems with known intrinsic size)
Cosmic Microwave Background Temperature Fluctuations

COsmic Background Explorer (COBE) satellite
version 2003

Wilkinson Microwave Anisotropy Probe (WMAP) satellite
What do we learn?

Different universes would leave different fingerprints
GEOMETRY OF THE UNIVERSE

OPEN
FLAT
CLOSED

Universes with different amounts of matter would distort the CMB radiation by different amounts
High redshift supernovae type Ia
The accelerating Universe!

Recession velocity (in km/sec)

Distance from the Earth (in billions of parsecs)
The proposed SNAP satellite

Supernova / Acceleration Probe

Studying the Dark Energy of the Universe
Cosmic Pie

- **Dark Energy**: 73%
- **Cold Dark Matter**: 23%
- **Atoms**: 4%
Towards a coherent picture: modeling structure formation in the Universe
A Brief History of the Universe
**Formation of structures**

- **Big Bang**
  - $z=10^{10}$
  - ![Big Bang Image]

- **First particles form**
  - ![First particles Image]

- **Light elements (H, He, Li) form**
  - $z=100000$
  - ![Light elements Image]

- **Universe becomes neutral**
  - $z=1000$
  - ![Neutral Universe Image]

- **First stars form**
  - Universe is reionized
    - $z\approx 10$
  - ![First stars Image]

- **Galaxies form**
  - $z\approx 1-5$
  - ![Galaxies Image]

- **Solar system forms**
  - $z\approx 0.4$
  - ![Solar system Image]

- **Present day**
  - $z=0$
  - ![Present day Image]
Computer Simulations: How to set up and where to begin?

If the content of the Universe is assumed, theory predicts the statistical properties of inhomogeneities in matter distribution.

these predictions are used to set up initial conditions of the simulations

Simple analytic predictions are accurate only while inhomogeneities are small (<10% fluctuations with respect to the mean density of the Universe).

simulations are initialized at an epoch before analytic predictions break down, during the so-called "Dark Ages"

Numerical simulations are used to follow formation of structures and make accurate predictions at later epochs where analytic calculations break down
Computer Simulations: How do we model?

- Gravity is the king
  
  *gravity is by far the strongest force on the large scales. gravitational interactions are modelled using Newton's laws*

- Other forces may need to be included depending on the composition of the Universe and scales considered

  *ordinary matter, the baryons, experiences pressure forces if compressed to sufficiently high densities. these "hydrodynamic" forces are included in simulations that include baryons*
We all live in

EXPANDING UNIVERSE
Computer Simulations: discretizing matter and space

- Space and time are continuous on macroscopic scales, but computers can only deal with discrete numbers.

- Memory and CPU speed limit the number of volume elements and particles that we can simulate.

  *In the standard theories, $10^6$ - $10^{12}$ dark matter particles are expected in a cubic Megaparsec.*

  *Current computers can handle only up to a billion particles.*

  ----> need to discretize
Hardware

Supercomputers at National Centers and Labs
(e.g., the National Center for Supercomputer Applications - NCSA)
www.ncsa.uiuc.edu

Lots and lots of storage...
Many Many Lines of Software

```fortran
subroutine Split ( Level, ntot )

purpose: splits cells marked to split
input: Level - level to process
output: ntot - # of cells just split

include 'a_def.h'
include 'a_tree.h'
include 'a_control.h'

integer ntot, Level
integer idxcell
real*8 xhi, yhi, zhi, xlo, ylo, zlo
real*8 xaxis(6), yaxis, zaxis
dimension iPyr(6*nchild,3) / interpolation pyramid vertices

! Warning! The loops below are to be executed SERIALLY

if ( Level .eq. Minlevel ) then
  do iicl = 1, ncell10
    if ( xsplit(iicl) .gt. wspl1 ) then
      ntot = ntot + 1
      iocl = iocl+1
      xlo = xhi(iocl)
      xhi = xhi(iocl)+0.0
    else
      hvar(4,iocl)+0
    end if
  end do
else
  if ( ( sta(1) .gt. eps ) .then
    rcl = (a1 + p .1 + b1) / ( p .1 + c1 )
    u2l = 1.0 / sqrt( max( small_R, rcl ) * s1l(2) + ( p .1 + s1l(3)) )
    u1l = s1l(2) + ( s1l(3) - p .1 ) * u2l
    x1l = ( a1 + p .1 + b1 ) / ( p .1 + c1 )
    wcl = 1.0 / sqrt( max( small_R, s1c * s1r(l) + ( p .1 + s1r(l)) )
    ur1 = s1c(2) + ( s1c(3) - p .1 ) * wr1
    p2 = max( small_R, 1.0000001 ) * p .1 - ( ucl - u1l )
    ! obs ( p .1 - p )
    ! / ( obs ( ur1 - ur )
    ! + obs ( u1l - ur0 )
    ! + obs ( ucl - ur0 )
    ! + small_R )
    p .0 = p .1
    p1 = p .0
    ur0 = ur1
    ur1 = ur1
    dev1 = obs ( p2 - p .1 ) / ( p2 + p .1 )
    stc(l) = dev1
    dev = max( dev, dev1 )
  end if
end if
if ( iter .ge. maxit .and. dev .gt. eps ) go to 1
endif

! End loops
!
if ( dev .gt. eps ) then
  write(*,'(2x, 'Riemann solver iteration failure') )
  stop
endif

State as x/s=0

u = 0.5 * ( u0 .0 + u .0 )
ind.i = int ( 0.9 - sign ( 0.5 , u ) )
cho_s = ind.i * ( s1c(l) - s1l(2)) + s1l(2)
vit .0 = 1.0 - ind.i * ( s1c(l) - s1l(2)) + s1l(2)
P .s = ind.i * ( s1c(l) - s1l(2)) + s1l(2)
Eqad .s = ind.i * ( s1c(l) - s1l(2)) + s1l(2)
con .s = ind.i * ( s1c(l) - s1l(2)) + s1l(2)
```

Universe in a box: formation of a filament
modeling formation of a galaxy cluster

10 million light years
Towards simulating realistic galaxies
A cluster or a galaxy?
Modeling the Local Group

computer simulation  The Local Group
Seeing back into the cosmos

HST GOODS / CHANDRA DEEP FIELD

JWST

Modern universe 13.7

First galaxies

First stars

Cosmic microwave background

Dark Age

Big Bang

Age of the universe (billions of years)

0.95

0.3

0.004 (~400,000 yrs)
Additional Reading

Slides of this talk:
http://astro.uchicago.edu/~andrey/talks/mysteries

Animations:
http://cfcp.uchicago.edu/1ss

Scientific American, February 2004

The Elegant Universe by Brian Greene, Norton, 2003
The Extravagant Universe by Robert Kirshner, 2002
Voyage to the Great Attractor by Alan Dressler, 1994

Map of the Universe:
www.astro.princeton.edu/~mjuric/universe

Wilkinson Microwave Anisotropy Probe:
map.gsfc.nasa.gov