Exploring the Invisible and Hot Universe:
A multi-wavelength view of galaxies and galaxy clusters

Spiral galaxy
Elliptical galaxy
Cluster of galaxies

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Light Year (ly): The distance light travels in one year (9,460,700,000,000 km)

Distance from Earth to Sun (AU) is about 8 light minutes
Spanning the Spectrum: Multiwavelength Astronomy

Our Sun

Radio

Visible

X-ray
Although X-rays and Gamma rays are very energetic, they are absorbed by the Earth’s atmosphere. Need to go into space.

Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gases (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.

Primary gases that are responsible for the atmospheric absorption of energy are water vapor, carbon dioxide, and ozone.
Early Evidence for Dark Matter

First suggested by Fritz Zwicky – 1933
Galaxies in the Coma cluster moving too FAST
Not enough visible matter to hold galaxies together
Cluster galaxies should just fly apart UNLESS the cluster is filled with 10 times more matter than seen in visible light!

Coma Cluster - 1000 galaxies
Each galaxy has 100 billion stars

ZWICKY KNEW!
Dark Matter In Galaxies

Vera Rubin showed that in spiral galaxies there is not enough luminous matter to hold the stars together. Instead about 10 times more dark matter, than luminous matter is needed to hold the stars together.

M51
The Whirlpool
A typical spiral galaxy
Dark Matter in Clusters of Galaxies
Could the missing matter just be hard to see?

at least some matter is “hard” to detect

Zwicky’s view of the Coma cluster

• Galaxies
• Stars
• Only about 2-5% of total mass

BUT THERE’S MORE THAN MEETS THE EYE
Clusters of galaxies

- Massive/gravitationally bound
- Galaxies - 2 - 5 % of total mass
- X-ray observations (first from Uhuru) found diffuse hot gas ($10^8$ K)
- Hot X-ray emitting gas ~15% of the total mass - most "normal" matter is hot gas.
- Most of the mass in clusters of galaxies is dark matter

Chandra X-ray image on optical field
X-ray Astronomy - from Sco X-1 to Chandra

- 1962 - Detection of first non-solar X-ray source Sco X-1
- First imaging solar X-ray telescope (Giacconi 1963)
  - About the same diameter and length as Galileo's 1610 telescope
  - 380 years later, Hubble is $10^8$ times more sensitive
- In 37 years X-ray astronomy achieved comparable increase in sensitivity with launch of Chandra (launched in 1999)
  - Largest/heaviest (22,000 kg) payload launched by shuttle (Chandra+IUS)
  - Orbit goes 1/3 of distance to the moon (64 hour orbit)
  - Power 2300 watts = 1 (good) hair dryer
Chandra X-ray Telescope

- Focus with two grazing incidence reflections (paraboloid/hyperboloid)
- Almost 20 sq m of area
- Mirrors are very smooth. If mirror were enlarged to size of Spain, largest "bump" would be < 1 cm high

- Detect individual photons (time, position, energy)
- Chandra designed for 5 years - almost 20 years (July 23, 1999 launch)
- Planning for another 10 years is underway!!!
The Bullet Cluster - X-ray and visible light
Dark Matter in Motion - The Bullet Cluster

- Visible image
- Galaxies, but nothing unusual

- Chandra X-ray image – shows the action
- Spectacular Merger at supersonic velocity

Hot gas moving through the dark matter at supersonic velocity of 3000 km/sec forms a Mach cone
Need to measure where the dark matter is

Background galaxies magnified and distorted by foreground cluster give direct measure of cluster mass
Gravitational Lensing

Add a black hole with the mass of Saturn over the middle of the Washington Mall, and view the Smithsonian Castle through the resulting gravitational lens.

Multiple images formed when alignment is not perfect.

From the MEFLIN homepage at <http://www.jb.mar.ac.uk/merlin>.

Through a gravitational lens.
Need to measure where the dark matter is

Background galaxies magnified and distorted by foreground cluster give direct measure of cluster mass
The Bullet Cluster

Red - hot gas
Blue - dark matter
The Bullet Cluster
What are clusters of galaxies made of?

1) Galaxies
2) Hot gas $10^8$ K
3) Dark Matter
MACS0717 - one of the richest, most massive clusters in the Universe.

Visible light image of HST frontier fields galaxy cluster MACS0717

Multi-wavelength observations are critical to understand cluster merging
Multiwavelength view of MACS0717

X-ray (hot gas, blue), radio (red) and visible light of rich cluster of galaxies.

Major merger of smaller clusters of galaxies.
Nobody knows what Dark Matter is.

- “Cold” – it falls into galaxies and into clusters

- Best guess – exotic particles from the very early Universe
  - WIMPS – weakly interacting massive particles
  - Examples - Axions, neutralinos

- Active searches to find this missing component of the Universe
Supermassive black holes lie at the centers of galaxies.

The more massive the dark matter halo, the more massive the black hole.

Our Milky Way is a spiral galaxy with a relatively small central bulge, and a relatively small black hole ($4 \times 10^6 M_{\odot}$).
Motions of stars around the Black Hole in our Galactic Center (Ghez+ 2008)
Centaurus A – the Nearest Radio Galaxy

Merger with gas rich galaxy
The X-ray Jet in Centaurus A

Simulation

Chandra Observation
Centaurus A in X-rays – Bubbles and Jets

- Counter-jet
- Southern lobe - sharp, smooth

Bubble diameter 3 kpc
“Bubbles” are not empty, but are filled with energetic particles and magnetic fields.
Clusters of Galaxies - Virgo Cluster - Optical

Central galaxy (M87) in Virgo cluster
Virgo Cluster - X-ray/Optical

- Extensive gaseous atmosphere
- $6 \times 10^9 M_{\odot}$ supermassive black hole in M87
- Ideal system to study SMBH/gas interaction
Chandra X-ray emission for M87 on optical field
X-ray Features in the Central Region of M87

- The X-ray jet
- X-ray cavities surrounding the jet and the (unseen) counterjet
- X-ray cavity associated with the ‘budding’ bubble to the S/SW
- Cavities/bubbles in the eastern arm
Chandra view of M87

“Raw” images
Just select different energy bands
See the over-pressurized regions = shocks

Matched scales

\[ \int P^2 dt \]
The M87 galaxy - Latest News!

Only resolved black hole image by Event Horizon Telescope (asymmetry from rapidly rotating plasma and relativistic beaming).

X-ray (soft)  X-ray (hard)  Optical

M87*  April 11, 2017

ISCO - innermost stable circular orbit
EHT Paper 1; fig. 3. 2019 ApJ L 875, 1
Rising bubble loses energy to surrounding gas

\[ f = \left( \frac{p_1}{p_0} \right)^{(\gamma - 1)/\gamma} \]

Generates gas motions in wake
Kinetic energy (eventually) converted to thermal energy (via turbulence)

\[ \Delta E_{\text{gas}} = -\Delta E_{\text{bubble}} = -\Delta \frac{\gamma}{\gamma - 1} PV = E_0 \left[ 1 - \left( \frac{P}{P_0} \right)^{1-1/\gamma} \right] \]

Bubble energy remaining vs. radius
~100 Myr - old (radio) bubbles

~40 Myr - torus & uplifted arms

~12 Myr - shock & initial cavity (still surrounds SMBH)

now - re-inflating cavity
Repetitive Radio Outbursts in M87

Energy input into the radio halo around M87 on three different time scales:

\[ \sim 10^8 \text{ yrs} \]

\[ \sim 10^7 \text{ yrs} \]

\[ \sim 10^6 \text{ yrs} \]

within \( \sim 40 \text{ kpc} \)

total energy \( \sim 3 \times 10^{59} \text{ ergs} \)

(= Sun’s total energy over its lifetime)
Family of early type Galaxies with hot gas
Evidence of Supermassive Black Hole Outbursts in Atmospheres

NGC4636 Galaxy
- 1 kpc
- $10^{56}$ ergs
- $10^{42}$ erg/s

Perseus Cluster
- 10 kpc
- $10^{59}$ ergs
- $10^{45}$ erg/s

MS0735 Cluster
- 100 kpc
- $10^{62}$ ergs
- $10^{46}$ erg/s

Powerful outflows from the SMBH
Little radiation from black hole - not the familiar “AGN”
Span a wide range of dark matter halo mass
Bubbles are very common across the mass range
Gas Rich Early Type Galaxies

As a class, luminous early type galaxies ($L_K > 10^{11} L_{\odot}$) have hot corona
• AGN outbursts, typical
• Massive galaxies do NOT have “dry” mergers
• Complementary view from optical
Dark Energy – Most of the mass-energy in the Universe

- Heavy Elements: 0.03%
- Ghostly Neutrinos: 0.3%
- Stars: 0.5%
- Free Hydrogen and Helium: 4%
- Dark Matter: 25%
- Dark Energy: 70%
Dark Matter and Dark Energy

Composition of Galaxy Clusters
- Dark Matter (x25)
- Hot Gas (x4)
- Stars/Galaxies (x1)

Composition of the Universe
- Dark Energy 73%
- Cold Dark Matter 23%
- Atoms 4%
Spectrum-Roentgen-Gamma (eRosita)

Launch 2019
All Sky Survey
Athena X-ray mission - launch 2028

More distant future
Lynx mission concept in a nutshell

- Ambitious concept for X-ray optics. Mirrors work at grazing incidence, and are tightly packed into a \(~3\text{m diameter}\) envelope. New technologies are needed for manufacturing such a mirror.

- We currently aim at \(~0.5''\) angular resolution (half-power diameter), detailed trades are pending.

- Focal length \(~10\text{m}\), providing 0.2–10 keV energy band.

- A suite of 3 advanced science instruments, with requirements TBD. Instrument Working Group is in place.
  - X-ray microcalorimeter array with \(~1''\) pixels
  - High-definition X-ray images (Si-based active pixels array)
  - X-ray gratings with high efficiency and spectral resolving power \(\geq 5000\)
If I had been present at the creation, I would have given some hints for the better arrangement of the Universe.

Alfonso the Wise - king of Castile and León (1252-1284), patron of the arts and learning

The most incomprehensible thing about the world is that it is comprehensible.

Albert Einstein
THANKS!