Astro 350

Lecture 40

Dec. 10, 2012

Announcements:

- Good news: now more homework!
- Bad news: Final Exam next Friday Dec 14, 8-11am here
- **ICES** available online – please do it!
  I do read and use comments!

Last time: cosmic structures and the inhomogeneous universe

Q: what happens after the first objects appear?

Q: bottom-up or top-down? why is structure formation "hierarchical"?

Testing Structure Formation

Q: what observations are available?

Q: what complications are there in comparing with predictions?
Hint–think about us:
at the location of the Milky Way, there was a "seed"
i.e., the density was higher than the cosmic average:
ρ(here) $>$ ρ(average) *Q: why?*

Q: so what determines what the cosmic density excess here?
Q: how does this complicate comparing predictions vs observations?

Testing Structure Formation

Observations:

▷ measure statistical properties of structures
$\delta\rho$ vs size
clustering: how many nearby neighbors?

▷ measure intergalactic gas
use quasars as backlighting

▷ measure dark matter
use gravitational lensing

Theory:

predict observable properties: where are the *galaxies?*

- analytic (pencil & paper) calculations as guidelines
- computer simulations for accuracy
  $\rightarrow$ UIUC, NCSA big players!

Present Status:

★ theory works well for large structures

intergalactic medium, clusters, superclusters

X problems with smaller structures

especially galaxy cores, dwarf galaxies

? trouble w/ observations or interpretation?

? oversimplified simulations?

? problems with WIMP dark matter?

stay tuned...

Gravitational Instability: Gas and Photons

Cosmic ingredients behave differently

• **dark matter** most of mass

weakly interacting $\rightarrow$ no pressure! begins collapse

galaxy "dark halos" form first!

$\rightarrow$ growing dark matter halos act as "gravity wells"
picture a cosmic " random egg crate"

dark halo formation begins when the cosmic matter density becomes larger than the radiation density:

• redshift $z \approx 3000$, time $t \approx 75,000$ years

• this is *before* recombination at $t \approx 400,000$ years

$\rightarrow$ dark halos form when baryons (mostly H and He) still *ionized*
photons constantly scattering in gas (plasma)

Q: what happens to baryons & photons?

competition:

outward expansion, pressure

vs

inward gravity

$\rightarrow$ like hydrostatic equilibrium in the Sun

consider an overdense region–growing dark matter halo:

- baryons & photons fall in $\rightarrow$ compressed
- higher density $\rightarrow$ higher T
- but higher T $\rightarrow$ *much* higher photon pressure $P \propto T^4$
- photons push outwards, scatter of gas and drag it out too
- "rebound," but slowed by halo gravity
- then fall back again again: *oscillations!*

Q: what happens when the plasma recombines $\rightarrow$ neutral?

Ringing in the Birth of Structure

before recombination:
baryons (= H and He gas) *ionized* $\rightarrow$ coupled to photons
oscillate in dark matter halos: compression $\leftrightarrow$ rarefaction
$\Rightarrow$ cosmic plasma "rings" like a bell!

after recombination:
baryons $\rightarrow$ neutral atoms, decoupled from photons

baryons no longer "feel" photon scatterings = pressure

- begin to fall into dark matter halos
- free fall until $v >$ sound speed
- shock waves form, gas slowed, heated $\rightarrow$ comes to equilibrium
  the first, smallest, protogalaxies formed!

photons no longer “feel” baryons, stream away from halos

- but are warmer than average due to compression
- oscillations “encoded” in photon temperature

$\rightarrow$ can observe this in CMB today!

`www: oscillation in CMB temperature pattern`

The First Stars

Consider:

- the present-day Universe contains stars
- the early Universe contained no stars

$\rightarrow$ there had to be *a first generation of stars*

Q: where are stars born today?

Q: when/where were the first stars born?

Q: what was the birth composition of the the first stars?

Q: how were the conditions for first star formation different from star formation today?

Star Formation Now and Then

Today:

- stars born in cold, dense-ish clouds of gas and dust
  "giant molecular clouds"
- heavy elements allows rapid cooling and fragmentation
- most starbirth in clusters, can range form 10s to 1000s of stars
- newborn star masses span wide range, but typically $M_\star < M_\odot$

In the early universe:

- first stars must still be born in cold, dense gas clouds
- but no heavy elements yet $\rightarrow$ no dust
- fragmentation probably (?) much more difficult

$\rightarrow$ first stars likely to be more massive stars
current best predictions: one huge star per dark halo
$M_\star > 10 - 100 M_\odot$!

`www: first star simulations`

Q: what happens if this is true?

The Imprint First Stars

If the first stars are ultra-massive

- *live fast:* give off huge amounts of light, mostly ultraviolet ionizes gas in halo and surrounding region
- *die young:* explode with huge energy enough to blow all gas out of the small gravity well of the low-mass baby dark halo
- *leave a beautiful corpse:* heavy elements ejected in explosions with unusual patterns

Result: if this is true, the first stars:

- are responsible for making the universe ionized once again
- which shuts down star formation for some time
- and seed much of the Universe with heavy elements
- that lead to more ordinary second-generation stars

The Cosmic Rise and Fall of Stars

Present day (and probably near future) telescopes
not yet powerful enough to see first-generation stars

But we *can* trace the history of star formation in the U
through the light of massive newborn stars in galaxies

`www: cosmic star formation history`

Results:

- star formation is ongoing today
- star formation was *more intense* in the past
  most stars in the Universe were born long ago
- cosmic star formation peaks at $z \sim 2-3$, 6-10 billion years ago
  elliptical galaxies, spheroids ("bulges") formed then
  thus most heavy elements made then
  Sun and Earth born about the time of peak star form!

FINALE

A Brief History of the Universe I

Speculations on the High-Energy Frontier

Planck Epoch: $t \sim 10^{-43}$ s

realm of quantum gravity

spacetime infected w/ quantum fuzziness (?)

black holes created and evaporated (?)

Inflation: $t \sim 10^{-38}$ s **(???)**

exponential expansion

quantum fluctuations $\rightarrow$ seeds of structure

Baryogenesis: $t \sim 10^{-37}$ s **(???)**

matter-antimatter asymmetry created

must occur after inflation (why?)

A Brief History of the Universe II

The Early Universe

Big Bang Nucleosynthesis: $t \sim 1$ s, $z \sim 10^{10}$

neutrinos freeze out, remain as cosmic neutrino background

light elements created

Matter-Radiation Equality: $t \sim 30$ kyr, $z \sim 3200$

matter density begins to exceed radiation density

$\rho_{\text{matter}} > \rho_{\text{rad}}$

expansion slows, structures begin to grow

Recombination: $t \sim 380$ kyr, $z \sim$ **1100**

plasma $\rightarrow$ neutral gas

opaque $\rightarrow$ transparent

CMB photons free stream

A Brief History of the Universe III
The Growth of Structure

The First Stars: $t \sim 100$ Myr, $z \sim 30$ **(???)**

very massive ($> 100 M_\odot$) $\rightarrow$ die as supernovae?

reionization of the universe?

Star Formation Peaks: $t \sim few$ Gyr, $z \sim 3$ **(??)**

elliptical galaxies, spheroids formed

Matter–Dark Energy Equality: $t \sim 4$ Gyr, $z \sim 1$

$\rho_{\text{dark energy}} > \rho_{\text{matter}}$

structure formation tails off

exponential expansion begins

Sun Born: $t \sim 9$ Gyr, $z \sim 0.5$

Planets formed soon thereafter

Today: $t \sim 14$ Gyr, $z \equiv 0$

You take Astronomy 350

www: Cosmic Wrongness--the votes are in!

Final iClicker Poll: Cosmic Surprises

Of the following aspects of modern cosmology

Which of these seems the most likely to be overturned?

A inflation

B matter-antimatter difference due to early universe particle reactions

C dark matter as fossil exotic particles

D dark energy as origin of cosmic acceleration

Which of these seems the most likely to be confirmed?

OPEN QUESTIONS

⋆ Why do most (all?) galaxies have black holes at their centers? What does this have to do with galaxy formation?

⋆ What is the origin of spiral, elliptical galaxies? What role do mergers, dark matter play?

⋆ What is the nature of the dark matter in the Milky Way? Can we detect it?

⋆ What is the nature of the dark energy? Is it related to inflation?

⋆ What is the fate of the U.? Are we doomed to exponential expansion and the cosmic "tunnel vision" of a shrinking horizon?

⋆ Did the universe undergo inflation? If so, what was the microphysics at work–i.e., what was the inflaton ϕ? If not, what is the origin of density fluctuations, and what solves the horizon and flatness problems?

⋆ Is the dark matter a relic particle leftover from the early U.?

⋆ Did the universe undergo a singularity at $t = 0$? What is the nature of quantum gravity and what does this mean for the origin of the U.?

⋆ Will all of this be on the final?

Thank You!