Astro 350

Lecture 30

Nov. 4, 2011

Announcements:

- HW 8 due now
- HW 9 available, due in 1 week
- Discussion Question 8 due next Wednesday

Last time: cosmic acceleration and the preposterous universe

Q: what's so bizarre about the universe is accelerating?

Q: what are the possible explanations for this?

Q: which solution is the least radical?

Q: what is Λ? how does it lead to acceleration?

Man, there's a lot of unexplained phenomenon
out there in the world.
Lot of things people say
What the heck's going on?
– Cosmologist Mojo Nixon

Cosmo-tip: acceleration is strange!

Expanding universe already a challenge to imagine
...now add acceleration on top of this!

if it doesn't bother you
you probably need to think harder about it!

The Onset of Acceleration

recall: supernova data show that

- the universe is *accelerating* now and in "recent" past in blatant contradiction to expectations
- but in more distant past, universe was *decelerating*

How can we understand this?

Example: if cosmological constant Λ, then

$$\text{acceleration} = \frac{\ddot{a}}{a} = -\frac{4\pi}{3} G\rho + \frac{1}{3}\Lambda \qquad (1)$$

Q: Which term is bigger today?

Q: what about the past–what is a like at earlier times?

Q: How does matter density ρ change in the past? Λ?

Q: and so what happens in the past? what about the future?

$$\text{acceleration} = \frac{\ddot{a}}{a} = -\frac{4\pi}{3}G\rho + \frac{1}{3}\Lambda \qquad (2)$$

today:

- U accelerating, so acceleration > 0
- and thus positive Λ term $>$ negative ρ term

in the past:

- scale factor a smaller (U is expanding!)
- Λ same, but matter density $\rho = \rho_0/a^3 \propto 1/a^3$
  $\Rightarrow$ in past, density higher: ρ bigger
- at some point in past (some value of a):
  negative ρ term wins $\rightarrow$ U decelerates!
- in fact, not long ago: terms equal when $a = 1/1.3 = 0.75$!

in the future:

- ρ keeps getting smaller, but Λ same
- acceleration becomes even more positive

$\Rightarrow$ a Λ universe will accelerate (and expand) forever!

Λ and the Cosmic Coincidence Problem

cosmo constant Λ – what *is* it?

- a new constant of nature (like c, G)
- can be viewed as "antigravity" source everywhere
- but also can be viewed as a "substance"
  filling all of space, at all times,
  with uniform density of energy $\rho_\Lambda = \Lambda/8\pi G$

"vacuum energy density"

curious fact: today $\rho_\Lambda \approx 2\rho_{\text{matter},0}$
but ρ_Λ never changes with U expansion
while ρ_{matter} always changes
$\Rightarrow$ so why do we live at a special time:
  almost at the moment when the two are equal?
at most cosmic times, either $\rho_{\text{matter}} \gg \rho_\Lambda$
  or $\rho_\Lambda \gg \rho_{\text{matter}}$

huge coincidence!? seems anti-Copernican! *Q: ways out?*

Dark Energy

to keep "spirit of Λ"
but avoid cosmic coincidence problem:

generalize vacuum energy idea $\Rightarrow$ **dark energy**

- previously unknown energy field ("scalar field")

  known matter and energy fields fail!

  have positive pressure and thus attractive gravity
- also has negative pressure, causes acceleration
- but now density can change – and usually does!

  $\rho_{\rm DE}$ can drop with expansion

  but in some models can even *increase*!

Dark Energy and Cosmic Coincidence

some dark energy models ("quintessence")
find dark energy change (evolution) is linked
to the rest of cosmic contents (matter, radiation)

evolution occurs in such a way that
always keep $\rho_{\rm DE}$ close $\rho_{\rm matter+rad}$
so this is *always* true, not just now
$\rightarrow$ alleviates cosmic coincidence
of acceleration starting "yesterday"

Dark Energy vs Cosmo Constant

technically: dark energy density $\rho_{\rm DE} \propto a^{-3(1+w)}$

with w unknown except that need $w < -1/3$ for acceleration

cosmological constant: $w = -1$ exactly, so $\rho_{\rm DE} \propto a^0 = const$

Note: cosmo constant is *special case* of dark energy

simplest possible version: unchanging always

Q: so how do we tell if we have Λ
or more general dark energy?

Q: and who cares? what's the difference?

Unmasking Dark Energy

cosmo constant is very special:
Λ and thus ρ_Λ strictly constant
never change in time or space

so if can measure cosmic expansion in past
can find the density needed to cause this
see if it changes or not

technically: measure w from $\rho_{\rm DE} \propto a^{3(1+w)}$

cosmo constant if and only if $w = -1$

Who cares?

- if Λ: why do we live at the moment
  it has revealed itself? Anthropic principle?
- if *not* Λ: what is this weird
  evolving dark energy that fills the universe?

iClicker Poll: Refine Your Bets on Cosmic Acceleration

What is causing cosmic acceleration?

A a cosmological constant Λ

B dark energy (but not special case of cosmo constant)

C modified gravity

Uh Oh.

Warning!
some dark energy models have ρ_{DE} increasing with time!
i.e., expansion $\rightarrow$ *larger* density of dark energy!?!
leads to scale factor growth

$$a_{\mathsf{future}}(t) \propto \frac{1}{t_{\mathsf{rip}} - t} \tag{3}$$

where $t_{\mathsf{rip}} > t_0$ is a fixed future time
Q: what happens when $t = t_{\mathsf{rip}}$? why is this bad?

The Big Rip

if DE density increases with expansion
then expansion rate $H \propto \rho_{\mathsf{DE}}$ accelerates more & more

$$a_{\mathsf{future}}(t) \propto \frac{1}{t_{\mathsf{rip}} - t} \tag{4}$$

diagram: plot of a vs t

- ▷ scale factor $a \to \infty$ at $t = t_{\mathsf{rip}}$
- ▷ in finite time, all particles move infinitely far from all other particles: **the big rip**

Cosmologists & Ghostbusters Harold Ramis & Bill Murray

Harold: `It would be bad.`

Bill: `I'm a little fuzzy on the whole "good/bad" thing here. What do you mean "bad"?`

Harold: `Try to imagine all life as you know it stopping instantaneously and every molecule in your body exploding at the speed of light.`

`www:` `Cosmologist Woody Allen,` *Annie Hall (1977)*

Cosmologist David Letterman reacts
From the Wahoo Gazette, July 23, 2003

Dave was enjoying a nice read of the New York Times after Tuesday's show when he came upon an article which claims the universe is splitting in two. Some "dark energy" is wrenching the universe apart.

Dave says "If the world and the universe is actually splitting apart like the New York Times says, then WHY IS IT ON PAGE 19? Shouldn't it be on Page 1?" For the rest of the program, everything seems minor and inconsequential considering that the universe is being pulled apart by a mysterious dark energy.

Living with Dark Energy

Current Data:
acceleration demands dark energy of some kind
cosmo constant is simplest version, but also works well
$\rightarrow$ no current data demand something more complicated than Λ
$\rightarrow$ but other dark energy models survive
$\rightarrow$ big rip not required or strongly favored, but also
can't be ruled out by current data!

Outlook:
most of universe dominated by a force/substance
we don't at all understand!
- major cosmo puzzle!
- upcoming projects to better measure "Λ,"
or whatever dark energy is...
or to uncover mistake! could this be our "ether?"

$\star$ either way Illinois a major player in making progress!