Exploding stars, distances to far away galaxies, and the composition of the universe

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The current view of the universe, encapsulated in the hot big bang model, seems popular. The above image is a screen grab from the theme song of the recent American sitcom ‘The Big Bang Theory’! 

1 See http://www.cbs.com/shows/big_bang_theory/.
The 2011 Nobel prize in physics was awarded to Saul Perlmutter of the University of California, Berkeley, U.S.A. (on the left), Brian P. Schmidt of the Australian National University, Weston Creek, Australia (in the middle) and Adam G. Riess of the Johns Hopkins University, Baltimore, U.S.A. (on the right) for the discovery of the accelerating expansion of the universe through observations of distant supernovae.

Plan of the talk

Outline

1. Runaway galaxies and the Hubble’s law
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2. The cosmological distance ladder
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Our galaxy – the Milky Way – as observed by the COsmic Background Explorer (COBE) satellite at the infrared wavelengths\(^3\). The diameter of the disc of our galaxy is, approximately, \(45 \times 10^3\) ly or \(15\) kpc (i.e. a kilo parsec). It contains about \(10^{11}\) stars such as the Sun, and its mass is about \(2 \times 10^{12}\) \(M_\odot\).

Our galactic neighbors and the local group

Left: The Andromeda galaxy and its two companion galaxies. The Andromeda galaxy is very similar to our galaxy and is located at a distance of about \( 700 \text{ kpc} \).

\[4\] Images from http://www.seds.org/messier/m/m031.html and http://www.seds.org/messier/m/m033.html.
Our galactic neighbors and the local group

Left: The Andromeda galaxy and its two companion galaxies. The Andromeda galaxy is very similar to our galaxy and is located at a distance of about 700 kpc.

Right: The Triangulum galaxy. These galaxies, along with our galaxy, are major members of a local group of about 30 galaxies that are bound gravitationally. The size of the local group is estimated to be about 1.3 Mpc.

Images from http://www.seds.org/messier/m/m031.html and http://www.seds.org/messier/m/m033.html.
Varieties of galaxies

Left: The disk galaxy NGC 4565 seen edge on in this image from the Sloan Digital Sky Survey (SDSS). The galaxy has a clear bulge, but little light can be seen from its halo.

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Center: An image of the spiral galaxy NGC 3187 from SDSS.

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Center: An image of the spiral galaxy NGC 3187 from SDSS.

Right: CGCG 180-023 is a superb example of a ring galaxy. Ring galaxies are believed to form when a compact smaller galaxy plunges through the center of a larger more diffuse rotating disk galaxy.

Continuous, emission and absorption spectra

A typical continuous spectrum from an opaque hot body:

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Emission spectrum, as from a given element:

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Continuous, emission and absorption spectra

A typical continuous spectrum from an opaque hot body:

Emission spectrum, as from a given element:

Absorption spectrum, as due to an intervening cool gas:

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Spectra of some spiral galaxies. The spectra usually contain characteristic emission and absorption lines.

7 Image from http://astronomy.nmsu.edu/nicole/teaching/ASTR505/lectures/lecture26/slide01.html.
The ‘Doppler effect’ and redshift

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The redshift $z$ of the receding source is defined as:

$$1 + z = \frac{\lambda_O}{\lambda_E} = \frac{\omega_E}{\omega_O},$$

where $\lambda_O$ and $\omega_O$ denote the observed wavelength and frequency of the source, while $\lambda_E$ and $\omega_E$ denote its emitted wavelength and frequency, respectively.

\[8\text{Images from http://www.astronomynotes.com/light/s10.htm.}\]
Runaway galaxies – A schematic diagram

A distant galaxy, $z = 0.25$

A farther galaxy, $z = 0.05$

A nearby galaxy, $z = 0.01$

A galactic star, $z = 0$

In the above spectrum of the galactic star, the wavelengths of the absorption lines are 393 and 397 nm from Ca II (ionized calcium); 410, 434, 486, and 656 nm from H I (atomic hydrogen); 518 nm from Mg I (neutral magnesium); and 589 nm from Na I (neutral sodium).

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Runaway galaxies – Actual observations

Spectra of four different galaxies from the 2dF redshift survey. On top left is the spectrum of a star from our galaxy, while on the bottom right we have the spectrum of a galaxy that has a redshift of \( z = 0.246 \). The other two galaxies show prominent H\( \alpha \) emission lines, which have been redshifted from the rest frame value of 6563 Å.

\( \text{Image from } \text{http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.} \)
Relation between the velocity and the distance of galaxies

Left: The original Hubble data. The slope of the fitted line is 464 km/sec/Mpc.

Right: A more recent Hubble diagram. The slope of the straight line is found to be 64 km/sec/Mpc.


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2. The cosmological distance ladder
3. Implications of the supernovae observations
4. Other supporting evidence
5. Summary and further reading
The baseline of the earth’s orbit of 2 Astronomical Units (AU) can be used to determine the distances of nearby stars through trigonometric parallax.

\[ \text{Image from http://find.uchicago.edu/~pryke/compton/slides2/mgp00007.html.} \]
The parsec

- **Parsec (pc):** The distance to an object whose parallax is 1″ due to the baseline of the earth’s orbit of 2 AU.
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From the figure in the previous slide, it is clear that

\[ d = \frac{1 \text{ AU}}{\tan p} \simeq \left( \frac{1}{p} \right) \text{ AU}, \]

where we have assumed that the angle \( p \) is small. If \( p \) is expressed in units of arc seconds, we find that

\[ d = \frac{2.063 \times 10^5}{p''} \text{ AU}. \]

Note that for \( p = 1'' \), \( d = 2.063 \times 10^5 \text{ AU} = 1 \text{ pc} = 3.26 \text{ ly} = 3.0857 \times 10^{16} \text{ m}. \]
Astrometry with Hipparcos\textsuperscript{13}

An image of the Hipparcos satellite which was the very first space mission for measuring the positions, distances, motions and brightness of stars. While distances up to $30\,\text{pc}$ were measurable from Earth using parallax, Hipparcos allowed determination of distances up to $100\,\text{pc}$ using the same method.

\textsuperscript{13}Image from http://www.rssd.esa.int/Hipparcos.
The concept of a standard candle

- For objects beyond 100 pc, direct measurement of distances turn out to be impossible (as the angles involved prove to be rather small), and one needs to resort to other methods.
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- Possible correlations between the intrinsic brightness and one or more easily observable properties of distant objects can help us arrive at their intrinsic brightness.
Left: Cepheid variables are stars whose outer atmospheres pulsate with periods of about 2-100 days. The observed magnitude of a Cepheid in the nearby Large Magellanic Cloud has been plotted as a function of time.
Cepheid variables – An important early rung

Left: Cepheid variables are stars whose outer atmospheres pulsate with periods of about 2-100 days. The observed magnitude of a Cepheid in the nearby Large Magellanic Cloud has been plotted as a function of time.

Right: The period of the oscillations of the Cepheids are found to exhibit a strong correlation with their intrinsic magnitudes. Such a correlation is initially established using nearby Cepheids whose parallaxes are known. Cepheids further away can then be utilized to determine distances up to a few Mpc.

Galaxies themselves as standard candles

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- Also, in the case of elliptical galaxies, it is known that there exists a specific relationship between the mean brightness of the galaxies and the dispersion in their velocities.
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- These properties can be used to determine distances of the order of 100 Mpc.
Construction of the cosmological distance ladder.

Assembling the cosmological distance ladder. A variety of well-established properties of stars and galaxies are used to construct the ladder\textsuperscript{15}.

\textsuperscript{15}Image from http://upload.wikimedia.org/wikipedia/en/1/13/Extragalactic_distance_ladder.JPG.
What is a supernova?

A supernova is an explosion of a massive, supergiant star, which may shine with the brightness of $10$ billion suns! The above image is a composite optical and x-ray image of the supernova remnant Cassiopeia A, and the bright source near the center is a neutron star, i.e. the incredibly dense, collapsed remains of the stellar core\textsuperscript{16}.

Type Ia supernovae are produced when material accrete on to a white dwarf from an evolving star as a binary partner. If the accreted mass causes the white dwarf mass to exceed the Chandrasekhar limit, it will catastrophically collapse to produce the supernova.

17 Image from http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html
Supernovae can be as bright as the host galaxy\textsuperscript{18}

Supernova 1994D, visible as the bright spot on the lower left, occurred in the outskirts of disk galaxy NGC 4526.

\textsuperscript{18}Image from http://apod.nasa.gov/apod/ap981230.html.
A supernova explosion in a distant galaxy\textsuperscript{19}

\textbf{Left:} A supernova at the redshift of 0.28 caught at maximum light by the Supernova Legacy Survey (SNLS).  
\textbf{Right:} The supernova after it has faded.

Light curves of type Ia supernovae

Top: Absolute magnitude, an inverse logarithmic measure of intrinsic brightness, is plotted against time (in the stars rest frame) before and after peak brightness. The great majority fall neatly onto the yellow band.

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Light curves of type Ia supernovae\textsuperscript{20}

\textbf{Top}: Absolute magnitude, an inverse logarithmic measure of intrinsic brightness, is plotted against time (in the stars rest frame) before and after peak brightness. The great majority fall neatly onto the yellow band.

\textbf{Bottom}: Simply by stretching the time scales of individual light curves to fit the norm, and then scaling the brightness by an amount determined by the required time stretch, one gets all the type Ia light curves to match, suggesting a standard candle. These supernovae can be used to determine distances in excess of 1000 Mpc.

Beyond the Hubble’s law

Determining luminosity distances of galaxies further away permits us to understand their behavior at large redshifts which, in turn, allows us to determine the matter content of the universe.

Image from http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html.
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Distribution of galaxies in the universe

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- The **Sloan Digital Sky Survey (SDSS)** is one of the most ambitious and influential surveys in the history of astronomy.
- Over eight years of operations, it has obtained deep, multi-color images covering more than a quarter of the sky and created three-dimensional maps containing more than 930,000 galaxies and more than 120,000 quasars.
The Friedmann-Robertson-Walker metric

The homogeneous, isotropic and expanding universe can be described by the following Friedmann-Robertson-Walker line element:

$$ds^2 = dt^2 - a^2(t) \left[ \frac{dr^2}{(1 - \kappa r^2)} + r^2 \left(d\theta^2 + \sin^2 \theta \, d\phi^2\right) \right],$$

where $t$ is the cosmic time and $a(t)$ denotes the scale factor, while $\kappa = 0, \pm 1$. 

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$^{22}$Image from http://abyss.uoregon.edu/~js/lectures/cosmo_101.html.
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where \( t \) is the cosmic time and \( a(t) \) denotes the scale factor, while \( \kappa = 0, \pm 1 \).

The quantity \( \kappa \) denotes the spatial geometry of the universe. It can be flat \((\kappa = 0)\), closed \((\kappa = 1)\) or open \((\kappa = -1)\) depending on the total energy density of matter present in the universe\(^{22}\).

\(^{22}\)Image from http://abyss.uoregon.edu/~js/lectures/cosmo_101.html.
The Friedmann equations

If $\rho$ and $p$ denote the energy density and pressure of the smooth component of the matter field that is driving the expansion, then the Einstein’s equations for the Friedmann-Robertson-Walker metric lead to the following equations for the scale factor $a(t)$:

$$H^2 + \frac{\kappa}{a^2} = \frac{8\pi G}{3} \rho \quad \text{and} \quad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p),$$

where $H = (\dot{a}/a)$ is the Hubble parameter.
A two-dimensional analogy for the expanding universe. The yellow blobs on the expanding balloon denote the galaxies. Note that the galaxies themselves do not grow, but the distance between the galaxies grows and the wavelengths of the photons shift from blue to red as the universe expands. 

23 Image from http://www.astro.ucla.edu/~wright/balloon0.html.
The cosmological redshift

Recall that, we had defined the redshift $z$ of a receding source as follows:

$$1 + z = \frac{\omega_E}{\omega_O},$$

where $\omega_O$ and $\omega_E$ denote the observed and emitted frequencies, respectively.
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In an expanding universe, by solving the geodesic equation, it can be shown that the frequency of photons decreases with the expansion as follows:

$$\omega(t) \propto \frac{1}{a(t)}.$$

Therefore, in terms of the scale factor, the cosmological redshift $z$ is given by

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It is important to appreciate that the redshift is not due to Doppler effect, but is cosmological in origin, arising due to the expansion of the universe.
The cosmological parameters

In terms of the redshift $z$, the first of the Friedmann equations can be written as

$$\left( \frac{H(z)}{H_0} \right)^2 = \Omega_{NR} (1 + z)^3 + \Omega_R (1 + z)^4 + \Omega_\Lambda - (\Omega - 1) (1 + z)^2,$$

where $H_0 \equiv (\dot{a}/a)_{t=t_0}$ is the Hubble constant, $\Omega_i = (\rho_i/\rho_C)$ with $\rho_C$ being the critical density given by

$$\rho_C = \frac{3 H_0^2}{8\pi G}$$

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The quantities $H_0$, $\Omega_{NR}$, $\Omega_R$ and $\Omega_\Lambda$ are four of the cosmological parameters that are to be determined by observations.
Abundance of light elements \(^{24}\)

The graph to the left contains the theoretically predicted abundance versus the density for the light elements as curves, the observed abundances as horizontal stripes and the derived baryon density as the vertical stripe. Note that a single value of the baryon density fits all the four abundances, and it is found that \(\Omega_B h^2 \approx 0.022\), which corresponds to only about 5% of the total amount of matter in the universe!

The spectrum of the Cosmic Microwave Background (CMB) as measured by the COBE satellite\(^{25}\). It is such a perfect Planck spectrum (corresponding to a temperature of \(2.725^\circ\) K) that it is unlikely to be bettered in the laboratory. The error bars in the graph above have been amplified 400 times so that they can be seen!

The extent of isotropy of the CMB

The fluctuations in the CMB as seen by COBE\textsuperscript{26}. The CMB turns out to be isotropic to one part in $10^5$.

Implications of the supernovae observations

The luminosity distance $H_0 d_L$ plotted as a function of the redshift $z$ for spatially flat cosmological models\textsuperscript{27}. The black points are from the ‘Gold’ data sets and the red points are the data from the Hubble Space Telescope\textsuperscript{28}.

\textsuperscript{27} Figure from T. R. Choudhury and T. Padmanabhan, Astron. Astrophys. \textbf{429}, 807 (2005).

The cosmic pie chart

![Pie chart of the matter content of the universe.](http://map.gsfc.nasa.gov/media/060916/060916_UniversePie300.jpg)

A pie chart of the matter content of the universe.

29 Image from [http://map.gsfc.nasa.gov/media/060916/060916_UniversePie300.jpg](http://map.gsfc.nasa.gov/media/060916/060916_UniversePie300.jpg).
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CMB anisotropies as seen by WMAP and Planck

Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data\(^{30}\).

The universe according to WMAP and Planck


Image from http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe.
CMB anisotropies as seen by WMAP and Planck

Left: All-sky map of the anisotropies in the CMB created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data\(^{30}\).

Right: The CMB anisotropies as observed by the more recent Planck mission\(^{31}\). The above images show temperature variations (as color differences) of the order of 200° \(\mu\)K. The angular resolution of WMAP was about 1°, while that of Planck was a few arc minutes. These temperature fluctuations correspond to regions of slightly different densities, and they represent the seeds of all the structure around us today.


\(^{31}\)Image from http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe.
The CMB TT angular power spectrum from the Planck data (the red dots with error bars) and the best fit ΛCDM model with a power law primordial spectrum (the solid green curve).

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Summary

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- These conclusions are independently supported by the observations of the anisotropies in the CMB.
Summary

- The supernovae observations point to the fact that the cosmological constant (or, in general, dark energy) and pressureless (i.e. cold) dark matter contribute about 70% and 25% to the density of the universe today, respectively.
- These conclusions are independently supported by the observations of the anisotropies in the CMB.
- A dominant dark energy implies an accelerating universe.
For further reading


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Thank you for your attention