SIZING UP THE UNIVERSE

THE COSMOS IN PERSPECTIVE

J. Richard Gott / Robert J. Vanderbei

http://www.sizinguptheuniverse.com
As Jupiter's moon Io transits in front of Jupiter, it can be seen against the upper layer of Jupiter's dense clouds below.
Can a photo of the sunset over Lake Michigan reveal the shape of our planet?
INTRODUCTION

HOW BIG ARE THINGS in the sky? It’s a child’s question, really, but one that has altered the course of civilization. When Aristarchus of Samos first figured out that the sun was bigger than Earth, in about 260 B.C., he correctly deduced that Earth must be orbiting the larger sun, rather than the sun circling tiny Earth. But people didn’t believe him. They followed Aristotle’s idea that Earth was at the center of the universe. It wasn’t until Copernicus published the same idea in 1543 that the concept began to be taken seriously. If people had believed Aristarchus in the first place, science would have been pushed forward by more than 1,700 years. Where might our civilization and technology be by now if people had just listened?

One of the exciting things about astronomy is just how big those things in the sky really are. The sun is so big that a million Earths could fit inside. And yet there are stars much larger than the sun. The distances between the stars and between the galaxies are truly humbling. Our tiny Earth is just a speck in the vastness of space. It tends to put things into perspective.

In Chapter 1 we start by showing how big things look in the sky. The sun and the moon are the same apparent size in the sky—each about one-half degree across. As they set, you can cover each of them with your thumb held at arm’s length. If you know how big something looks and how far away it is, you can figure out its real size. Multiplying an object’s apparent size by its distance gives its actual size. Although the sun and the moon appear to be the same size in the sky, the sun is actually 400 times farther away, so its actual size is 400 times larger than the moon—a simple concept but an important one.

Astronomers typically learn how big an object looks by taking its picture through a telescope of known power. Then when we learn how far away it is, we can determine its actual size. Thus, we begin with side-by-side pictures of the sun and moon, showing how big they look. Then we show a series of ever more magnified views of objects through ever more powerful telescopes. As we continue our observing tour, we will show you how big things would look through the Hubble Space Telescope.

Then, in Chapters 2-4, we show where things are in the sky and how far away they are, keyed to discoveries by the ancient thinkers who were not as far off in their calculations as one might expect. Some of their methods are still in use today. And, in Chapter 4, with the conceptual framework firmly established, we offer a “map” of the universe, showing everything from satellites in Earth’s orbit to distant stars and galaxies, all on one fold-out section almost 40 inches tall.

Once we know how big things look, and how far away they are, we can show the actual sizes of things in Chapters 5 and 6. Chapter 5 shows sizes of things in the solar system. Hurricane Katrina is compared with a centuries-old storm on Jupiter called the Great Red Spot. In Chapter 6 we start with an actual-size picture of Buzz Aldrin’s footprint on the moon and end with the largest known object in the cosmos. If you are someone who likes to look at the last page of a mystery novel to find out the answer, and you want to know about the real sizes of things, you can skip directly to Chapters 5 and 6.
In cosmology, we are dealing with very large distances and very long times. When we measure the age of the Universe, we are measuring the time it took for the Universe to expand from a very small, high-density state to its current size. This expansion is due to the Big Bang, which occurred about 13.8 billion years ago. The age of the Universe is determined by the rate of expansion and the rate of acceleration.

The age of the Universe is not constant; it is a dynamic process that changes over time. The current rate of expansion is determined by the density of matter and energy in the Universe. The density of matter and energy in the Universe is not uniform; it varies from place to place. This variation in density is the cause of the acceleration of the Universe.

The density of matter and energy in the Universe is determined by the mass-energy content of the Universe. The mass-energy content of the Universe is determined by the distribution of matter and energy in the Universe. The distribution of matter and energy in the Universe is determined by the gravitational forces that act on the matter and energy in the Universe.

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Years ago, when I started astronomy, many young people were discovering it as a backyard hobby. You could see the wonders of the universe—from planets to galaxies—all from your backyard. But our increasingly bright city lights over the years have brightened the sky so much that the galaxies have faded from view. We call this phenomenon light pollution. To see anything but the brightest objects in the night sky you now have to go to a dark site. The backyard hobby became one where you needed to drive to a remote location and stay all night. As a result, it became a hobby for adults. Like skiing, it had cool equipment, but while better skis might make you only a slightly better skier, a bigger and more expensive telescope would allow you to see a lot more. So Vanderbei caught the wave of adults becoming amateur astronomers.

Vanderbei is also part of the making of a new hobby—astrophotography. The new digital cameras available today allow you to take long-exposure photographs and use filters to overcome light pollution. You can take photographs from your backyard that will show things you would never be able to see through the telescope. The galaxies are back! For the moon and planets, a simple webcam attached to a small telescope allows you to take videos of these objects and select the best frames (those least affected by atmospheric distortion) for producing your picture.

Vanderbei has taken all of his photographs from his backyard in light-polluted New Jersey. He took a beautiful picture of the lunar crater Plato using only a 3.5-inch-diameter telescope and a simple webcam. His photographs appear throughout this book along with the best NASA photographs, as noted in the illustrations credits. I have had the good fortune to travel around the world and see a number of its wonders, from the Taj Mahal to the Great Pyramid, and one of my joys was taking pictures along the way. But Vanderbei can take pictures of the wonders of the universe without ever leaving home. Vanderbei sets his telescope tracking a galaxy for an hour exposure and goes inside to watch television while it takes the picture. He can then download the picture to his computer and sharpen it with software or combine it with other exposures to make a brighter image.

Astronomy has become a computer hobby. Young people today are experts at downloading digital photographs onto their computers. We hope that this book, by showing what can be done from the backyard with a digital camera and a telescope, will help lure young astronomers back, for it has once again become a backyard hobby. With that in mind, Vanderbei has written an afterward with some of his thoughts on astrophotography, hoping that some of our readers will be encouraged to size up the universe for themselves.

Whether this is your first book on astronomy or you have read many, there should be some surprises here. (For example, I myself was surprised to see just how big the Ring Nebula is—I had thought it was about 23 times smaller.) Whether you are 16 years old or 60, whether you enjoy looking through a telescope or are just a curious armchair astronomer who has heard of black holes and wants to know more, this book was made for you. I hope you will find learning about sizes in the universe just as fascinating as I did once, so long ago.

—J. Richard Gott

Vanderbei captured this photo of the Eagle Nebula (opposite) with a 10-inch-diameter telescope from his backyard. For comparison, the famous Hubble Space Telescope picture of the Eagle Nebula is shown inset. The Hubble picture has more detail, having been taken from the vacuum of space, but the colors in Vanderbei’s photograph are more realistic—the nebula is actually red.
The Orion Nebula is an enormous cloud of gas and dust that is slowly condensing over the course of millions of years into stars. The stars we see are young. Come back in a few million years, and there will be more.
JUXTAPOSITIONS

IN THE NEXT FEW PAGES, we show a sequence of ever more magnified views of the sky with the moon arbitrarily placed as a template in each picture for comparison. In this way we can illustrate the angular sizes of various objects as seen from Earth. We begin by showing you how the moon would look if it ever wandered up near the Big Dipper, which it doesn’t. The moon is just one-half degree in diameter. In contrast, the pointer stars of the Big Dipper (the two rightmost stars in this picture) are five degrees apart, or about ten lunar diameters.

The apparent sizes of objects in the sky are measured by the angles they span in our field of view. A full circle spans 360 degrees. The horizon is a full circle on the celestial sphere, so a complete panorama around the horizon spans 360 degrees. You have to turn in a complete circle to view the entire horizon.

It was the ancient Babylonians who first divided the circle into 360 degrees. Since the sun has an angular size of half a degree (that’s 1720th of a full circle), it takes up just 1720th of the horizon when it sets. Each day, the sun moves about one degree in the sky relative to the stars. As Earth circles the sun each year, the sun appears to circle the sphere of stars once a year. While a year is actually about 365.25 days, the Babylonians chose to divide the circle into 360 degrees because it is conveniently divisible by many numbers. Their definition of the degree stuck.

The moon may look large when seen setting against distant houses and trees along the horizon, but at arm’s length, your thumb will still completely cover it. Half a degree is not very large. A typical digital camera in snapshot mode without zoom has an angular field of view of about 45 degrees. That means that it takes about eight pictures to stitch together a complete 360-degree panorama of the horizon. At a half degree wide, the moon takes up only 1/90th of the width of a typical digital camera field of view. That’s why the moon may appear surprisingly small in your snapshots.

The moon is the astronomical object closest to Earth. Astronomers measure distances by how long it takes light, traveling at 300,000 kilometers (or 186,000 miles) per second, to cross those distances. The distance to the moon is 1.3 light-seconds.

When Apollo astronauts on the moon talked to President Richard M. Nixon, you could hear 2.6-second delays in the conversation. That is, it took the radio signals carrying Nixon’s voice 1.3 seconds to travel to the moon and 1.3 seconds for the astronauts’ replies to get back.

The stars in the Big Dipper are much, much farther away. Their distances range from 78 light-years to 124 light-years. That means that we are seeing these stars not as they appear today, but rather as they appeared 78 to 124 years ago.

The illustration opposite shows how the moon would look if it ever wandered up near the Big Dipper (which it doesn’t). Viewed from a reading distance of about 17 inches, the angular scale is that of a normal naked-eye view from a dark site. The magnification is 1x; in other words, one times the magnification you see with the naked eye.
Aldrin’s Footprint

FOR OBJECTS OF EVEN SMALLER angular size, we show an even more magnified view. Alpha Centauri can be seen peaking in at the side. Proxima Centauri, its companion, and the closest star to Earth, is also shown. It is a red dwarf star. The star HD 209458 is a star similar to our sun but considerably farther away than Alpha Centauri. It has a Jupiter-like planet that transits in front of it, which we show in the illustration opposite. Astronomers measured that planet’s size by observing how much the luminosity of the star was dimmed as the planet passed in front of it.

FYI: A telescope with a magnification of 14,000,000× would be able to give you a good view of a quarter from a distance of 4,000 miles as you get from holding it in your hand.

Finally, we can see Buzz Aldrin’s footprint on the moon. It should still be there to observe. If we could get above the perturbing effects of Earth’s atmosphere and if we had a telescope about 40 kilometers (25 miles) wide, we could see it this well.

We have now had a look at the entire sky. One way to put it all in perspective is to think of the celestial sphere as it might be mapped onto or overlaid on a globe of Earth. In this projection, the band of light we call the Milky Way would encircle it, tracing a circumference of some 40,000 kilometers (25,000 miles). The Big Dipper would be almost as large as the continental United States. The image of the Andromeda galaxy would be about the size of New Jersey. The images of the sun and moon would each be 56 kilometers (35 miles) across, about the size of a large metropolitan city. Jupiter’s image would be seven-eighths of a mile across. Alpha Centauri’s image would be only 25 centimeters (10 inches) across, and Proxima Centauri’s image would be 3.0 centimeters (1.2 inches) across.

Now that we understand the apparent sizes of objects in the universe as seen from Earth, we are on a better footing to discover their actual sizes, which we will come to in Chapters 5 and 6. But first, in the following chapter, we will show how and where one can find these objects in the night sky.
What’s Above the Horizon?

Half the Celestial Cube is always above the horizon. If you are at mid-northern latitudes (approximately 45° north) and you go out at midnight on December 21, here is what you will see: Toward the north you will see the north circumpolar stars. The north celestial pole with Polaris, the North Star, will be about 45° above the northern horizon. The north circumpolar stars will extend from the northern horizon to the zenith (overhead). The winter stars will extend from the southern horizon to the zenith. The bottom of the winter star chart will sit on the southern horizon. The celestial cube will hang over you like a pop tent (below, and right). On the next page, in the top-left perspective drawing looking into the cube, as in the big diagram on the previous page, the part of the sky seen in winter at midnight is the black area enclosed in the trapezoid. Areas below the horizon are blue. The north and winter stars can be seen, as can half of the autumn and spring stars. The four sides of the trapezoid represent the northern, western, southern, and eastern horizons, clockwise from bottom.

Similar effects occur in the other seasons as indicated opposite. The visible part of the sky rotates during the year. March 21 at midnight shows the north and spring stars, June 21 at midnight shows the north and summer stars, September 21 at midnight shows the north and autumn stars. The north circumpolar stars are always visible bordering the northern horizon.

A celestial cube oriented for winter observing from mid-northern latitudes (left) hangs like a pop tent over the observer who is inside the tent on the ground at the center of it, looking up. Half of the cube is “below the horizon” and so not visible. Black regions (opposite) represent parts of the celestial cube visible at different times of the year from 45° north latitude on Earth. The blue areas are below the horizon. In each case, as in the previous page, the perspective view is looking into the cube.
Summer

At midnight on June 21 from mid-northern latitudes, these stars are visible above the southern horizon. The ECLIPTIC is the yellow line passing through SAGITTARIUS and SCORPIUS. THE MILKY WAY is prominent in the summer. THE RING NEBULA, the double star ALBEDRO, and the DUMBBELL NEBULA are great objects to view with small telescopes.
SUNSPOT COMPARED

4,330 km

Sunspot

SUNSPOT COMPARED

U.S.A.
CANYONS COMPARED

Valles Marineris

Grand Canyon

1094 km
STORMS COMPARED

Hurricane Katrina

Great Red Spot

4,370 km
LAKES AND VOLCANOES COMPARED

- Lake Michigan
- Methane Lakes on Titan
- Volcano on Io
- Hawaiian Islands
- Olympus Mons on Mars
EXOPLANETS COMPARED

Planets are shown to scale in silhouette against their stars as if seen in transit. The sun and its planets, Pluto, and some moons are shown for comparison. We can discover the sizes of extrasolar planets by noting the fraction of their star’s light they block if they transit in front of it. Most planets discovered to date are very close to their stars and hence too hot to allow liquid water on their surfaces. Planet HD 209458b is a hot gas giant planet like Jupiter. Planet GJ 436b is a hot Neptune-like planet. It’s hot because it is so close to its star, even though that star is a cool M-dwarf. CoRoT-7b is the smallest transiting planet discovered so far—it’s diameter is only 1.7 times greater than Earth’s diameter. It is a rocky planet with a temperature of more than 1,000 K.

GJ 436
CoRoT-7
Sun (for comparison)

HD 209458

508,000 km
Step Ten

ONE LAST JUMP by a factor of a thousand, and we can see the extent of the entire visible universe—everything we can see. We are looking here at the equatorial slice of the Sloan Survey containing 126,594 galaxies and quasars. It is a cross-sectional slice of the universe extending outward from Earth’s Equator. Earth is in the center of the picture. Galaxies are shown as green dots, and quasars as orange dots. The two large, blank regions are zones of avoidance, where our galaxy blocks the distant view. The scale shows the look-back-time distance in billions of light-years.

When we look out in space, because of the finite velocity of light, we look back in time. A galaxy five billion light-years away we see as it was five billion years ago. We can see out to a radius of just 13.7 billion light-years in any direction, because the universe began in a big bang explosion 13.7 billion years ago. The farthest thing we can see is the cosmic microwave background radiation left over after the big bang, which encircles the visible universe.

Earth is at the center of the visible universe. This does not mean that we are in a special location. If you look out from the top of the Empire State Building in New York City, the region you can see, out to the horizon, is circular and centered on the Empire State Building. Looking out from the top of a different building, you would see a different circular region—one centered on it. An observer in a distant galaxy would see a different visible region of the universe, one centered on his galaxy instead of ours. Most of the galaxies visible are less than 5 billion light-years away, while most of the quasars are between 5 and 12 billion light-years away. Near Earth, many voids and walls of galaxies are visible. These also appear in the Map of the Universe shown on pages 125-126.

The Sloan Great Wall (highlighted by a detailed, same-size inset that points to its location in the map) is the largest structure we have found in the universe so far. Its length stretches 1.37 billion light-years, one-tenth the radius of the visible universe.

The visible universe is very large because gravity is such a weak force. In 1961, physicist Robert Dicke pointed out that it is no accident we live about one stellar main-sequence lifetime after the big bang—after some stars have died (to make the carbon needed for life) but before all the stars have burned out, making it too cold for life. If gravity were stronger, main-sequence lifetimes of stars would be shorter, we would live closer in time to the big bang, and the radius of the visible universe would be smaller. Since gravity is weak, we carbon-based life-forms, orbiting our main-sequence star, are treated to a truly grand view.

Just think: After the end of inflation, the process that produced the big bang explosion 13.7 billion years ago, all the matter we can see in the visible universe today was still inside a region smaller than Buzz Aldrin’s footprint.

FYI We are now observing a scale a billion, billion, billion times larger than Buzz Aldrin’s footprint. And that footprint is a billion times larger than a hydrogen atom.
And Beyond

WHAT’S BEYOND the visible universe? Galaxies and more galaxies for a long way beyond the boundary of what we can see. Measurements of the cosmic microwave background by the WMAP satellite have enabled us to survey accurately the visible universe. The results tell us that a slice through the universe at the present epoch appears flat, like a sheet of paper. Keep extending a flat sheet of paper, and it forms an infinite flat plane. That might suggest the universe is infinite, with an infinite number of galaxies. Actually, it just means that the universe is much larger than the part we can see. Manhattan looks flat but actually is part of the finite, but large, curved surface of Earth. The universe could be almost any shape, but if it is large enough, any piece of it will look flat. All we really know for sure is that the true size of the universe is much larger than 13.7 billion light-years. Alan Guth’s theory of inflation predicts this, but how much bigger is it?

Physicist Andrei Linde’s theory of chaotic inflation suggests that our universe today may be 10^{100} times larger than the part we can see. Our universe forms in a high-density inflationary sea of dark energy. This dark energy has a very large negative pressure, and the repulsive gravitational effects of this pressure start a runaway expansion. This sea doubles in size every 10^{-36} seconds. Such a sequence (1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, . . .) blows up quickly. Inflation in our region ends when the dark energy converts into thermal radiation (the hot big bang) and the explosive expansion starts to slow down. Each funnel represents an inflating universe that is growing larger with time—we show one dimension of space (the circumference of the funnel) and the dimension of time (running upward out the funnel). We label four universes 1, 2, 3, and 4, from left to right. Universe 2 gives birth to universes 1 and 3—they are its children. Universe 3 gives birth to universe 4. So universe 4 is the grandchild of universes 1, 2, 3, and 4, from left to right. Universe 2 gives birth to universe 4. So universe 4 is the grandchild of universe 2. Each branch grows to infinite size and sprouts branches of its own. The process, once started, continues forever, producing an infinite fractal tree with an infinite number of branches.

FYI According to Linde’s theory, it would take over 10,000 more pictures, each covering a scale a thousand times larger than the one before, to capture our universe in its full glory.

Our universe is just one of many on one of these branches. We will never see these other branches, because the space separating us from them is expanding so fast that light can never cross it. Where did the trunk come from? Perhaps it simply popped into existence by a process called quantum tunneling, as proposed by Alex Vilenkin. Or perhaps it formed from a time loop, as proposed by me (Gott) and Li-Xin Li, when a branch looped back in time to grow up to be the trunk. We simply don’t know. Superstring theorists Paul Steinhardt and Neil Turok have suggested that our universe is a three-dimensional membrane floating in a ten-dimensional space and that the big bang occurred when our membrane collided with another.

If our universe is a bubble, it is infinite in extent. Beyond our universe, myriad other universes in the multiverse branch off in the distance, farther than the eye can ever see.

The space-time diagram above shows the Gott-Li model for the creation of multiple universes from a time loop. Each funnel represents an inflating universe that is growing larger with time—we show one dimension of space (the circumference of the funnel) and the dimension of time (running upward out the funnel). We label four universes 1, 2, 3, and 4, from left to right. Universe 2 gives birth to universes 1 and 3—they are its children. Universe 3 gives birth to universe 4. So universe 4 is the grandchild of universe 2. Each branch grows to infinite size and sprouts branches of its own. We live in one of the many branches. Physicist Andrei Linde has shown that, once started, this branching process will continue forever, creating an infinite fractal tree of universes.

The Gott-Li model represents just one of a number of speculative possibilities being explored by physicists for the origin of our inflating universe. Studies of the cosmic microwave background suggest that inflation is likely, but details of how it got started have yet to be worked out.

But where did the original trunk come from? Alex Vilenkin, Stephen Hawking, and James Hartle suggest it simply pops into existence. But Gott and Li have proposed that universe 2 was its own mother, giving birth to a branch that circled back in time and grew up to be the original trunk.
ALL IN ONE

AS WE HAVE SEEN, astronomers mapping the uni-
verse are confronted with the challenge of showing a
wide variety of scales. What should a map of the universe
include? It should show locations of all the famous things
in space: the Hubble Space Telescope, satellites orbiting
Earth, the moon, the sun, planets, asteroids, Kuiper belt
objects, stars such as Alpha Centauri, black holes, gal-
axies, quasars, and finally the cosmic microwave back-
ground radiation itself.

We want our Map of the Universe to display clusters of
galaxies, but also stars within our own galaxy and the
sun, moon, and planets. Objects close to us may be
inconsequential in terms of the whole universe, but they
are important to us. This calls to mind the famous New
Yorker cover of March 29, 1976, "View of the World from
9th Avenue" by Saul Steinberg, which humorously depicts
a New Yorker's view of the world. The traffic, sidewalks,
and buildings along Ninth Avenue are visible in the fore-
ground. Behind is the Hudson River, with New Jersey as
only a thin strip on the far bank. At even smaller scale, we
see the rest of the United States, with the Rocky Moun-
tains sticking up like small hills. In the background, but
not much wider than the Hudson River, is the entire
Pacific Ocean, with China and Japan in the distance.

This is, of course, a parochial view, but it is just the kind
of view that we are looking for. For our Map of the Uni-
verse, we would like a single map that would show equally
well both interesting objects in the solar system, nearby
stars, galaxies in the local group, and large-scale galaxy
clustering out to the cosmic microwave background.

Armed with the standard cosmological model from
the Wilkinson Microwave Anisotropy Probe (WMAP),
we can plot the expansion of the universe as a
function of time. For the first time, we have fairly accu-
rate knowledge of the geometry of the universe and the
distances to individual galaxies and quasars, so we can
plot a map of where they will be on a certain date.

In 1972, while I (Gott) was a graduate student, I
invented a map projection for the universe and produced
small versions of it over the years. Confronted with the
task of displaying the galaxy-clustering data from the
 Sloan Digital Sky Survey, Mario Juric and I decided that
it was time to make a large-scale detailed version of my

Map of the Universe to summarize all the exciting new
discoveries that had been made recently in astronomy.
The map projection I had devised was conformal, pre-
serving local shapes, as the Mercator projection does,
while still allowing us to cover the wide range of scales—
from Earth's neighborhood to the cosmic microwave
background. We include all objects known within two
degrees of the celestial equator—plus famous objects
above and below the celestial equator.

The WMAP satellite data tell us that the geometry
of such a two-dimensional cross section taken through
the universe at the present epoch (using co-moving dis-
tances) is flat like a piece of paper. The map of the universe
shows a 360-degree panorama from left to right, looking
out from Earth's Equator, while the vertical coordinate
shows distance from Earth. Earth's surface is a horizontal
line at the bottom of the map, and the cosmic microwave
background is at the top. As you move up the map, you
get farther and farther from Earth. The left- and right-
hand borders coincide; they could be taped together to
display the map as a cylinder. The horizontal coordinate
is celestial longitude (which divides the 360-degree view
into 24 hours—each hour covering 15 degrees).

Lines fanning out from Earth's Equator. Like edges of a
pizza slice, are shown as parallel vertical lines in the map.
Imagine a round piece of pepperoni sitting on a slice of
pizza just wide enough to span the width of the slice (above
left). The slice gets wider the farther it gets from the pie's
center, so if there was another piece of pepperoni farther
out that also spanned the pizza slice, it would have to be
bigger. Those two pieces of pepperoni would be shown with
the same width on the map because they cover the same
angle as seen from the center of the pizza. In our pizza slice
we show three pieces of pepperoni. The first one, nearest
the center, is the smallest. The second one is twice as big as
the first, and twice as far away. The third is twice as big as
the second and twice as far away. Now, usually a pizza will
have pieces of pepperoni that are all the same size, but in
our special pizza, the pepperoni pieces get bigger farther
out. The strip on the right shows our map projection of
the same pizza slice. Radical lines, the edges of the wedge-
shaped pizza slice, show up as vertical lines on the map.

If the map is to be conformal, showing local shapes
well, then the pepperoni pieces should all be shown as

Saul Steinberg’s famous New Yorker cover (opposite) provides
an illustration of scale, as does a slice of pepperoni pizza (above
left). The same slice after applying a logarithmic conformal map
(above right).
Let The Movie Begin
Let The Movie Begin
Let The Movie Begin
Let The Movie Begin