INTERACTIONS IN OUTER SPACE

How the Universe reveals itself

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From the discovery of alien worlds and the creation and evolution of galaxies to the reality of a dark side to the universe, cosmic interactions have been the golden key for unlocking many secrets about the universe. Through different examples, this article highlights how interactions between objects of outer space have constantly fulfilled our longing to make sense of the world around us.

Outer space is a lonely place. Stars are separated from each other, for the most part, by sheer emptiness. To appreciate how far apart things are in the universe, consider this example. Imagine the Sun as the centre of an expanding sphere. This imaginary sphere will have to grow to a radius of 38,000,000,000,000 kilometers before it can make contact with its **nearest** star. And that can take no less than about 4 years, even if the sphere were to expand at the speed of light!

The matter that does exist between stars is in a very diffuse state. The interstellar (space between stars) matter is so scattered around that on average there is barely about 1 atom per cubic centimetre of it. This is roughly thousand times wispier than even the best vacuum produced in laboratories here on Earth. Going by such staggeringly low numbers, it is easy to think of outer space as a tranquil world, where everything is isolated from the rest.

Interestingly, while the universe may not be a place of great turmoil, it is not a place of stagnation either. Even in this seemingly desolate space, many interactions occur, often in very significant ways.

These interactions are possible as a result of one of the most pervasive forces in the universe. This attractive force exists here on Earth, as well as in outer space. It can act between any two objects with mass - be it particles, people or planets. For two objects to feel this force, they do not have to come into physical contact with each other. The force can act even over extremely large distances. By now, you may have guessed, and guessed it right that we are referring to the force of gravity, one of the four fundamental forces in the universe (see Box 1).

Box 1. Physicists have grouped forces in Nature into four fundamental categories. These are the weak force, the strong force, the electromagnetic force and the gravitational force. Of these the weak and the strong forces are of significance only when we are describing interactions at scales smaller than the size of an atom. Gravity (and electromagnetic forces) on the other hand, can act over vast distances - from very near to very far, and between all masses - from atomic particles to giant galaxies. This attribute of gravity makes it the force that predominantly shapes our physical universe and governs its course of evolution. Gravitational interaction is also what allows us to study the properties of the universe in great detail.

For a short description of the four fundamental forces, see: http://www.quirkyscience.com/four-fundamental-forces/, or this http://shasthram.com/youngscientist/fundamental-forces-of-nature.

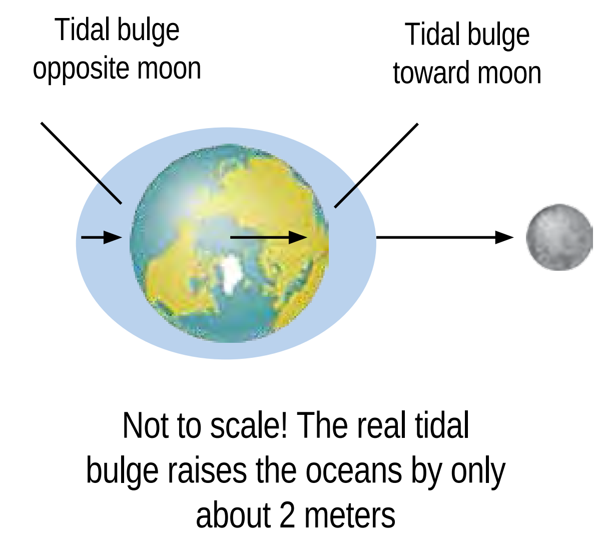


Figure 1. The formation of tides on Earth as a result of the Moon's gravitational pull. Source: Bennett et al.

Heavenly interactions are less obvious to us because, firstly, they happen out in the far depths of space, away from our usual gaze. Secondly, the time scales over which these interactions unfold, as we will see later, are not of the order of seconds, minutes, hours or a few days. Certain interactions are so dreadfully slow that it would take several human life times to perceive the outcome. Yet scientists have taken great pains to understand these interactions, not just because they are fascinating, but because they offer very useful insights into the way our universe works. This article highlights a few different scenarios of cosmic interactions, played out on different physical scales, from the astronomically small to the very large, from the very near to the very far.

Interactions within our neighbourhood

Let us start with an example that is simple and familiar.

At just over 400,000 kilometers, the Moon is a place not too far from home. Of all the celestial objects we are familiar with, the Moon (along with the Sun), has the most bearing on life here on Earth. People who live along coastlines are well aware of how tides turn strong twice every day and more aggressively so during the new moon every month. Interestingly, the rise and fall of tides have very little to do with anything internal to the ocean. That the high and low phases of tides coincide with certain specific phases of the moon indicates that it is the interaction of the Moon with the Earth that is the basis of existence of tides (refer Fig. 1). This interaction is through the force of gravity.

The water in the Earth's ocean on the near side (i.e., the side of the Earth closer to the Moon) gets pulled by the Moon's gravity, thus causing the water in the ocean to bulge out. But this water is also simultaneously getting pulled back by Earth's gravity, causing it to lash out on the sea shore as high waves.

Interestingly, a similar bulge also develops on the opposite side of the Earth. Unlike on the near side, this bulge is caused by inertia. Unlike solids, water is sluggish in movement. If you have ever played with water in a cup, you may have noticed this yourself. As you move the cup, the water in it shows a tendency to stay behind. Similarly, as gravity causes the Earth to feel a drag towards the Moon, the water in the ocean shows a tendency to stay where it is. The result is a tidal bulge on the far side (the side of the Earth that is not facing the Moon).

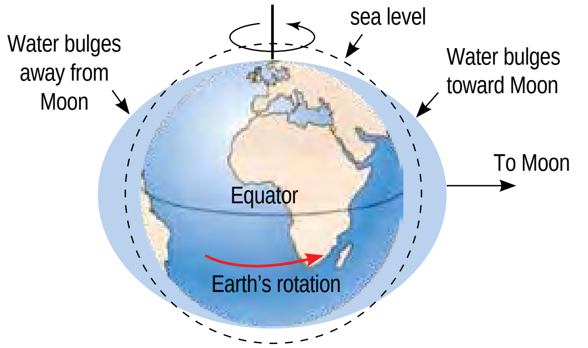


Figure 2. The Earth's rotation ensures that all geographical locations experience high tides.

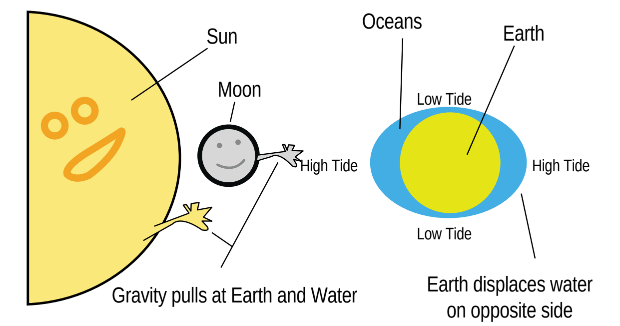


Figure 3. The most intense high tides are formed during the New Moon Phase, when the Moon and the Sun are on the same side of Earth.

The Earth's rotation ensures that all geographical locations experience these two tidal bulges once during a day–night cycle (refer Fig. 2). Thus, every coastline on Earth will face high tides twice in 24 hours. Of course, not all coastlines will experience the same intensity of tides. The force of tides will also depend on the shape of the coastline, the strength of winds, ocean currents and other, more local, factors. We have attempted to explain only the most dominant among these factors in the formation of tides.

Box 2: Gravitational forces are always attractive. The force of gravity between two or more objects depends on the mass of each object and the distance separating them. Expressed mathematically:

$$\mathbf{F = G\,M\,m/r^2}$$

M and **m**, here, are the masses of the two objects and **r** is the distance between them. G is a constant number, called the universal gravitational constant. From this equation it is evident that the gravitational force between two objects weakens as the separation between them increases. Similarly, if the objects are tiny in their mass (atoms, for example), then the gravitational force between them is going to be feeble even when they are very close to each other.

Suggested Task for Students: Keeping **M** and **m** as fixed values, and assuming G = 1, ask students to plot a graph that shows how the force of gravity between the two masses would vary with increase in distance between them. This can be done in an excel sheet.

What about the gravitational interaction of the Sun with the Earth? Is that of any consequence for tides on Earth? As it turns out, the Sun plays a lesser role in the ebb and flow of tides. Though a million times more massive than the Moon, the Sun's gravitational tug on Earth is only one-third that of the Moon because of the Sun's greater distance from us (see Box 2).

Try out this interactive animation on tides, from the University of Nebraska, to understand the effect of the Moon and the Sun on Earth's oceans: http://astro.unl.edu/classaction/animations/lunarcycles/tidesim.html.

Interestingly, tides become most intense when the Sun and Moon are aligned on the same side of the Earth (as shown in Fig. 3.). This is because the Earth now experiences gravitational forces from both the Moon and the Sun, acting in the same direction. This occurs every new moon; thus the tides at this time of the year are at their maximum intensity.

Interactions aiding our search for alien worlds

From the immediate reaches of our solar system, let us turn our attention to a different example, to a different physical scale, where observing the gravitational interaction between astrophysical objects have yielded some captivating discoveries about worlds beyond the solar system, some similar to Earth, and some very different.

Of all the big questions that human kind has ever been interested in, the most fascinating one is – are we alone in this universe? Can life emerge and evolve beyond the confines of Earth? Could there be other worlds, beyond the solar system, teeming with life? Generations of humans have speculated on questions like these. But it has only been in the last 20 years or so that we have made some scientific forays into answering them.

At present, we have no strong evidence for the presence (or absence) of life beyond that on Earth. But scientists realize that the first indication of life may be in finding an environment outside the Earth that is suitable for life. Life, as we know it, requires the comforting settings of a planet - a thick atmosphere, presence of liquid water, and a steady source of energy in the form of light and heat from a star. With these prerequisites in mind, the search for life elsewhere is presently focused on discovering planets around other stars.

Finding extra-solar planets (planets outside the solar system, also called exoplanets) is a very challenging task. Firstly, even the nearest stars are several light years (a light year is the distance that light travels in one year. Light travels through empty space at a speed of 300,000 kilometers every second. One can easily calculate how many kilometers a light year would be) of distance from us. At these distances, stars look like dots even through telescopes, not to mention their planets, which are typically a few hundreds to a few thousand times smaller than stars. Secondly, a star is a billion times brighter than a planet. What this means is that when we look at a distant star–planet system, for every billion photons (light particles) we receive from a star, one photon reaches us from the planet. The contrast in difficulties is similar to searching for a fire-fly (planet) next to a flood light (star).

Thus, snapping a photograph of an extra-solar planet with a telescope and a camera is rarely feasible. Does this mean that we can never hope to find planets beyond the solar system? Fortunately not! As it turns out, the interactions between a planet and its host star offer us some alternative ways of discovering them.

We generally understand a star-planet system as one where the planet is revolving around the star. But gravitational interaction is mutual. The planet will also exert some amount of gravitational force on the star. If the planet is sufficiently massive and close to the star, this force can be large enough to compel the star to move from its position (see Box 2).

Here is how this happens: in any star–planet system, the star and the planet orbit around a common centre. The common centre is the point where the mass of the star and the planet would be evenly balanced, as if they were on a see-saw. This common center is called the center of mass (see Box 3). The center of mass can be offset from the center of the star. As the planet revolves around the star, the star in turn moves around the center of mass in a periodic manner. As seen from telescopes on Earth, the star would appear to vacillate back and forth. By carefully measuring this wobbly motion of the star, astronomers are able to infer basic attributes of the extra-solar planet, such as its mass, the time it takes to complete one full revolution around the star, the planet's orbital distance from the star, and so on. What is important to remember is that we are not looking at the extra-solar planet directly; instead we are inferring its presence by observing the effect of the planet's gravitational interaction with the star.

Using this technique, in 1995, astronomers discovered the first planet outside of the solar system - around a star called 51 Pegasi, which is about 50 light years from us. Since then, the numbers of extra-solar planet detections have rapidly increased. Today, we know of the existence of more than 2000 planets beyond the boundaries of the solar system, orbiting various stars in our Galaxy. Most of these discoveries have happened because we are able to observe stellar wobbles caused by the gravitational interaction of planets around them.

Astronomers are now of the opinion that planets are widespread in our universe. Most stars possibly have one or more planets circling around them. Discovering these planets is just a matter of making careful observations.

The recent flurry of scientific discoveries of exo-planets has rekindled a lot of hope and hype on the possibilities of finding life elsewhere in the universe. If planets are as common as stars in our universe, couldn't there be at least one resembling our Earth, with a protective atmosphere, liquid water on its surface, and other conditions conducive for complex life? If conditions are favourable, can life emerge spontaneously in these other worlds? Can there be other sentient beings like us in some of these alien worlds asking such profound questions? We do not know yet, but thanks to gravitational interactions we at least know that there exist worlds beyond the solar system that are potentially habitable. That's one step closer to the answer.

Box 3. To understand where center of mass falls for a two-body system, consider the following example. Take two spheres of the same mass. If the spheres were pegged onto the ends of a rod, where would you support the rod for the weight of the spheres to be evenly balanced? Common sense tells us that it will have to be at the centre of the rod, half way from either sphere.

What if one of the spheres happened to be 10 times more massive than the other? You will have to support the rod at a distance 10 times closer to the more massive sphere to balance the system. If you provided support at any other point, the configuration will not be stable.

Mathematically, the center of mass is the point where:

Mass of object 1 x distance from center of mass to object 1 = Mass of object 2 x distance from the center of mass to object 2

$$m \times a = M \times b$$

Let us now look at a star–planet system. In a typical star–planet system, the star is most likely several thousand times more massive than the planet. Thus, the center of mass will have to be closer to the star compared to the low mass planet for the configuration to be stable.

From the equation, we can see that the location of the center of mass is going to depend on the ratio of the mass of the star to the planet. The higher this ratio, the closer the center of mass is to the star. In some cases, the ratio will be such that the center of mass will be within the star.

Since the star and the planet have to circle the center of mass, the lower mass planet will assume a larger orbit and the higher mass star a smaller orbit. For the system to be dynamically stable, the star and the planet have to beat opposite sides of the center of mass, at all times (see Fig. 4). For this to happen, the time it takes for them to complete one full orbit around the center of mass has to be the same. In other words, the planet has to move faster, and the star slower.

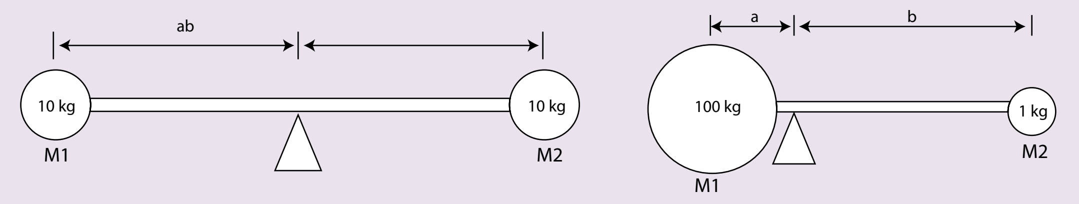
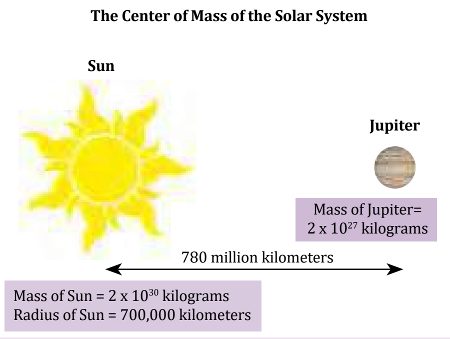


Figure 4. What is/isn't allowed for dynamic stability.

Refer this website for an interactive tool on the concept of center of mass: http://astro.unl.edu/naap/esp/centerofmass.html And this one for an illustrative video on the stellar wobble and how astronomers use it to discover extra-solar planets: https://www.youtube.com/watch?v=rN7uuqLKv0I

Suggested activity: It is easy to calculate the centre of mass of any system. As an example, try to find out where the centre of mass of the solar system is? To keep the calculation straightforward, think about only the two most massive objects in the solar system, the Sun and the planet Jupiter. Jupiter, though a huge planet when compared to Earth, is still a thousand times less massive than the Sun. Thus, we should expect the centre of mass of the solar system to be closer to the Sun. Use the information given in the graphics to figure out where the centre of mass of the solar system could be.



Galaxies and their violent interactions

From extra-solar planets, let's journey further out to the scale of galaxies, and witness some, more dramatic, interactions at a much larger scale. Galaxies are huge collections of stars. A galaxy like the Milky Way typically has about a few hundred billion stars within it. A countless number of such galaxies exist in our universe – differing widely in their size, shape and brightness. Astronomers spend a lot of time trying to understand how different galaxies have acquired these shapes (see Box 4).

Box 4: Shapes and sizes of galaxies: The way the stars are distributed within a galaxy gives it its particular morphology. Over the years, astronomers have made several attempts at classifying galaxies based on their observed shape. Based on their work, the two predominant classes of galaxies are:

a. Spirals: galaxies that have a disk-like shape with a spiral sub-structure to the disk.

   Visit this site to see beautiful pictures of spiral galaxies: https://www.noao.edu/image_gallery/spiral_galaxies.html

b. Ellipticals: galaxies that have an elliptical or spherical shape. Unlike spiral galaxies, elliptical galaxies are pretty much featureless. They look like a ball of stars.

   Here's an image gallery of elliptical galaxies: https://www.noao.edu/image_gallery/elliptical_galaxies.html

Other than their acquired shape, there are plenty of differences between spiral galaxies and elliptical galaxies. Astronomers are still trying to understand these differences. By looking at a large number of galaxies and their mutual gravitational interactions, astronomers have come to the conclusion that interactions between galaxies play a crucial role in the shapes they assume.

In the immensity of space, some galaxies are found in isolation, while most galaxies tend to huddle in groups. Within a volume spanning a few million light years, it is common to find several thousand galaxies together (see Fig. 5.). They are held this way by their mutual force of gravity. Such collections of galaxies are called galaxy clusters. There are many such clusters in our universe.

Figure 5. This is a Hubble Space Telescope image of the Coma cluster, a cluster of galaxies roughly at a distance of 320 Million light years from us. Every elongated source of light we see in this picture is a galaxy with countless billions of stars within it. The galaxies in this cluster are relatively near each other in space (astronomically speaking) and therefore are moving under the influence of each other's gravitational force.

Each galaxy within a cluster gets pulled on by the other galaxies within the cluster. This means that these galaxies cannot remain stationary. They move in random directions, constantly steered by the combined gravitational pull of all the other galaxies that belong to the cluster.

Movement in an overcrowded environment can often lead to unpleasant scenarios. For example, two or more galaxies can bump into each other. The outcome of such encounters is often spectacular. Astronomers have found numerous examples of galaxies in a cluster engaged in such interactions (refer Box 5). Such galaxy–galaxy interactions are sometimes loosely termed as collisions, which is not really the best word to describe them. The word 'collision' conjures up an image of some very violent and rapid phenomena. In reality, interactions between galaxies are slow, and for the most part, not very violent.

Galaxies are large structures, with a lot of empty space between stars. When they run into each other, individual stars in either galaxy are unlikely to collide with each other. Instead, much like the tides in the Earth's oceans, gravitational forces tug and drag interstellar gas clouds and stars away from their position, creating long tails, streams and plumes (remember, gravity can act over huge distances without physical contact). This is similar to a gravitational tussle, a kind of slow tearing apart of either galaxy engaged in the tidal interaction.

Figure 6. This image shows two spiral galaxies that are at some stage of interaction with each other. Such interactions often result in the creation of tail-like features, as seen in this image. These features are formed by streams of stars and interstellar gas dragged out from each galaxy because of their mutual gravitational pull. Although the two galaxies are moving with speeds of several thousand kilometres every second, because of their large sizes and the large distances that separate them, the entire interaction happens over time scales of several millions of years. Credits: Hubble Space Telescope.

Astronomers therefore prefer to call such interactions - mergers. Tidal tails (as seen in Fig. 6) are a tell-tale feature of interacting galaxies.

These interactions can often cause vast distortions in the structure of galaxies. When two spiral galaxies merge fully with each other, the resultant galaxy will be a bigger, more massive galaxy without any distinct sub-structure (like an elliptical galaxy). Could the elliptical galaxies that we see in the universe therefore be a product of the mergers of spiral galaxies? Observational evidence seems to suggest this. By studying galactic interactions, astronomers are learning new facts on how galaxies acquire their peculiar shapes, and how those shapes evolve over astronomically long periods of time.

The dark side of the universe

We now move to one final example of cosmic interactions. This is also the story of one of the current big mysteries in astronomy. There is mounting evidence suggesting that most of our universe is made of some kind of exotic matter that does not shine, or cast any shadow. It does not interact in any other way with the universe, except via gravity. No one has any specific idea about what it is, and yet we know it exists everywhere. To find out how astronomers came about discovering this mysterious component of the universe, we need to go back to the galactic clusters that we talked about in our last example.

In the early 20th century, the astronomer Fritz Zwicky (refer Fig. 7.) carried out some painstaking measurements on the speed with which galaxies were moving inside a cluster. For his study, Zwicky chose one of the nearby galactic clusters - the Coma cluster (refer Fig. 5).

Zwicky knew that each galaxy's motion was due to the gravitational pull that it felt from the total mass within the cluster. Thus, he deduced that by measuring the speed of different galaxies, he would be able to infer the total mass of all the galaxies of the cluster.Zwicky

Figure 7. Fritz Zwicky was a famous Swiss-born American astronomer who made several brilliant discoveries and predictions, including the gravitational effects of dark matter. For most of his career, he served as faculty at the California Institute of Technology. For a brief biographical sketch of Zwicky, refer: http://www.slac.stanford.edu/pubs/beamline/31/1/31-1-maurer.pdf

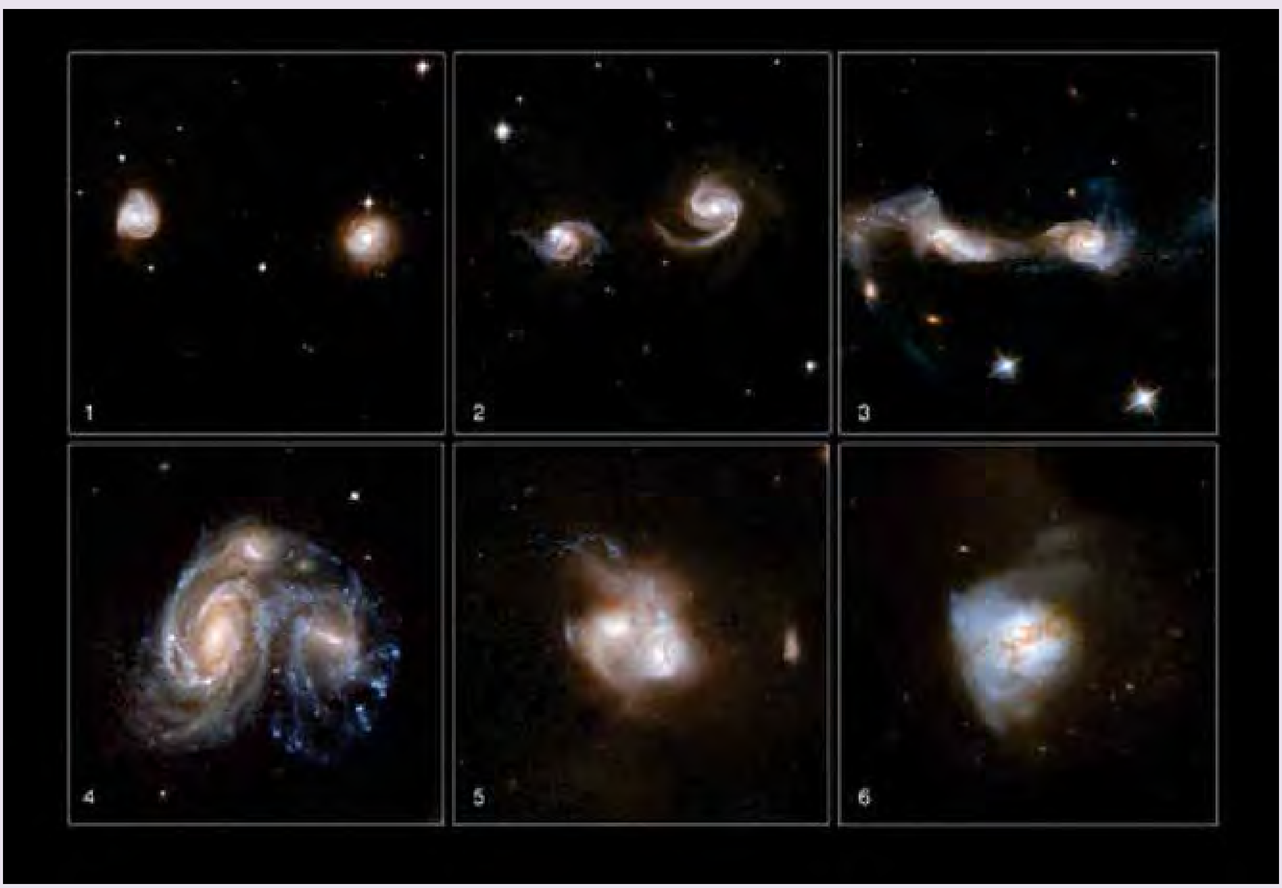
Box 5: Each panel here shows two spiral galaxies at a certain stage of their gravitational interaction. The images in the panels are not of the same set of galaxies. The six images have been picked from a larger collection and arranged in this order to give a visual sense of what happens when two galaxies approach each other. One can see that even before merging, the galactic shapes begin to get distorted. This is because of gravitational force, acting over a distance (much like the tidal force). In the last panel, the material belonging to both interacting galaxies merge together into one amorphous galactic structure. With the passage of time, this mass may evolve into a big elliptical galaxy.

Interactions between galaxies, like the one shown here, are slow processes, unfolding over several millions of years. No one is granted that luxury of time to stand and stare. When we survey galaxy clusters at different locations in the universe, we see galaxies at various stages of their merger. Like filling in a jig-saw puzzle, astronomers piece together such bits of information from different parts of the universe to create a working model on how galactic interactions play out in the universe. Astronomers also use the power of supercomputers to artificially recreate galaxy interactions. There are many wonderful animations available online showing galaxy mergers. Here are some examples:

http://hubblesite.org/newscenter/archive/releases/2002/11/video/a/

http://www.ifa.hawaii.edu/~barnes/transform.html

https://www.youtube.com/watch?v=HP3x7TgvgR8 – This last one may be particularly interesting in offering computer visualizations of what could happen during the merger of Milky Way and Andromeda, the big galaxy nearest to us.



made careful observations. From the random motion of galaxies, he calculated an estimate for the total mass contained within the Coma cluster (the so-called **dynamical mass**). To his amazement, the number he came up with was much larger compared to the total mass that one would arrive at by adding up the individual masses of all the stars in all the galaxies that belonged to the cluster (in other words, the mass that was emitting light, the so-called **luminous mass**). The dynamical mass was as much as a factor of 200 more than the luminous mass.

This mismatch left astronomers at a loss. The only way it could be explained was if there was considerable matter within the cluster that was gravitationally interacting with all the galaxies in the cluster. But this extra matter must not be emitting light, and had to be invisible to telescopes, or else we would have found it already. This invisible matter is what is now referred to as 'dark matter'. We now also know that despite moving very fast, galaxies that belong to a cluster remain confined to the cluster only because of the presence of dark matter. The extra gravitational pull of dark matter keeps galaxies from flying apart. This holds true not just for the Coma cluster, but almost every other cluster that astronomers have looked at.

Since Zwicky's pioneering observations, there have been other lines of evidence suggesting that dark matter is ubiquitous. It is the stuff that binds galaxies together, by surrounding them. Careful estimates have also shown that this dark matter far exceeds the amount of ordinary matter that we see in the universe. Thus, whenever we turn our telescopic gaze towards the night sky, we have to remind ourselves that all the illuminated objects that we see are just the tip of the iceberg. In fact, galaxies are like tiny light bulbs hanging on big trees. In darkness, we see the light bulbs, but not the trees.

So what is this dark matter? We do not know the answer to that question yet. Scientists are still speculating on what dark matter could be. It remains one of the biggest unsolved mysteries of modern science. And that's okay, because science is not always about finding quick answers. It is also about searching for new questions. The discovery of dark matter has opened up a lot of questions for which answers are, as it seems, not going to be easy. But scientists are excited because it has fashioned new pathways for research in physics.

What is certain about dark matter is that it cannot be matter made of particles such as protons and neutrons and electrons, the stuff of which you, I, and all the matter that we see around us are made. It has to be something else, a new kind of matter perhaps. Beyond that it remains a mysterious entity, at least for now. But thanks to their gravitational interactions with ordinary matter, we at least know that there is much more to our universe than what meets our eyes.

References and useful links

1. An interactive tool that explains and demonstrates the formation of tides: http://www.pbs.org/wgbh/nova/earth/what-causes-the-tides.html.
2. An online application that simulates the working principle behind the detection of extra-solar planets: http://astro.unl.edu/naap/esp/detection.html.
3. Galaxy Collider is an interactive tool that allows you to run toy models of galaxy merges with different starting conditions: http://viz.adrian.pw/galaxy/. Clicking and dragging on a blank area starts this simulation. Understanding how this tool works may require a bit of exploring.
4. The Cosmic Cocktail – Three Parts Dark Matter, by Katherine Fresse, Princeton University Press, ISBN 978-0691153353, is a recent popular science book that describes the fascinating story behind the discovery of Dark Matter and the our recent search to understand them.
5. The Crowded Universe, by Alan Boss, Basic Books, ISBN 978-0465009367, is a popular science book on extra-solar planets and the possibility of finding other Earths.

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