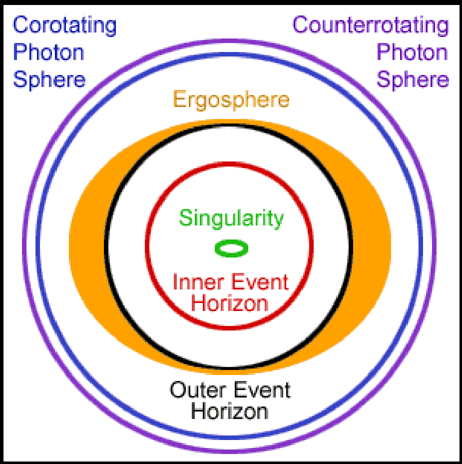
Upcoming Astronomy-themed Talks and Events

Thursday, 2/20, 3:45-5:00p Astronomy Colloquium – Phys-Astr A102 – Anthony Pullen (NYU) – “Line Intensity Mapping: Modeling & Analysis in the Precision Era”.

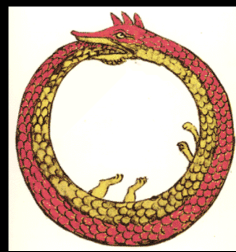
Last time we focused our attention on some of the most mysterious objects nature has to offer: black holes. They form whenever mass becomes sufficiently dense – and its affect on spacetime so strong – that light and all physical events near it become hidden behind an ‘event horizon’.



‘Schematic’ of the interior of a ***rotating*** black hole – any questions?

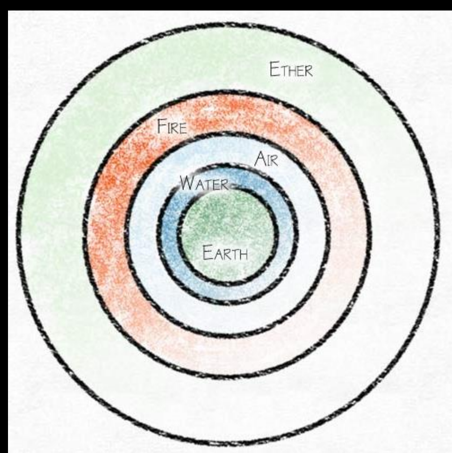
That event horizon, as defined by the so-called ***Schwarzschild Radius***, is rather small for most black holes – from a few dozen to a few hundred miles across. But it scales upwards with mass (3km wider for every solar mass worth of material) – and today we’ll see that some black holes are very, very large indeed!





What is that thing in the sky? The mythos of ancient peoples varied, and included many variations on rivers, spilt breast milk, and “world encircling snake-like beast” – although as early as 400 BC the Greek astronomer Democritus proposed that it was made up of numerous stars, unfathomably distant.

However, by 400 AD these ideas had been largely supplanted by the Aristotelian theory that the Milky Way was the result of “the fiery exhalation of some stars” which “takes place in the upper part of the (Earth’s) atmosphere”.



A model of the Aristotelian cosmos – the Milky Way is somewhere in that “Fire” region.

Abū Alī al-Ḥasan ibn al-Ḥasan ibn al-Haytham, circa 1000 AD.

This incorrect notion persisted until approximately 1000 AD, when it was debunked by the great Arabian astronomer Ibn al-Haytham (known as “Alhazen” in Europe).

He was amongst the very first to consider the physics of starlight in detail, and is generally considered to be the founder of the modern science of optics.

He noted that observations of the Milky Way from widely separated places on Earth showed no parallax with respect to the (presumably more) distant stars. The Milky Way therefore ***could not be*** in the Earth’s atmosphere.

The next real breakthrough came in 1610, when Galileo turned his newly constructed telescope to the Milky Way, and found it was indeed filled with faint and incredibly distant stars. This key observation supported the heliocentric model of the Solar System, by explaining the lack of observed stellar parallax – but it said little about the structure of the Milky Way or the Sun's location in it.

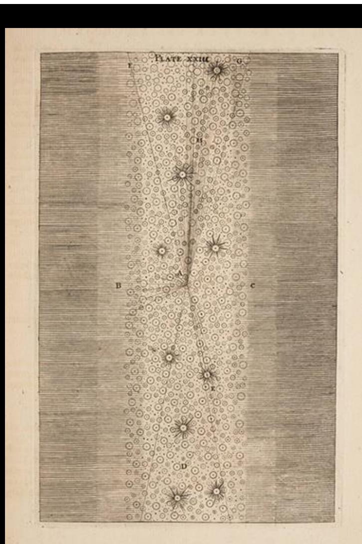


Plate from Thomas Wright's 1750 book suggesting the Sun embedded in a thick region of stars as a source of the Milky Way's appearance.

In 1755, the German philosopher Immanuel Kant, influenced by the work of Thomas Wright, proposed that the Milky Way was in fact a ***disk*** of stars, rotating and held together by gravity in much the same manner as the solar system. However, he believed the Sun was near the middle of this disk – and it's extent was uncertain.

It was not until around 1918, when Harlow Shapley mapped the distribution of *globular clusters* in our galaxy, that the true shape of the Milky Way began to be apparent. Shapley noted that the Milky Way’s globular clusters formed a (very!) rough sphere, with a center in the direction of Sagittarius.

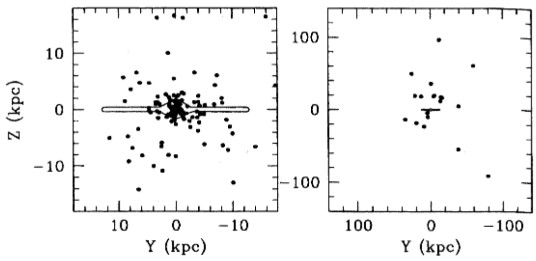


Fig. 2. *Left panel:* Spatial distribution of the inner globular cluster system of the Milky Way, projected onto the YZ plane. Here the Sun and Galactic center are at $(0, 0)$ and we are looking in along the X–axis toward the center. *Right panel:* Spatial distribution in the YZ plane of the outer clusters

A modern interpretation of Shapley’s map of Globular Clusters, projected onto a plane (from Harris, 2001).

The distribution of globular clusters around a different galaxy.

While Shapley overestimated the distances to the globular clusters (and therefore to the center of the Galaxy) by a factor of a few, for the first time in human history – and less than 100 years ago!! – we had finally discerned the true shape and general size of our galactic home.

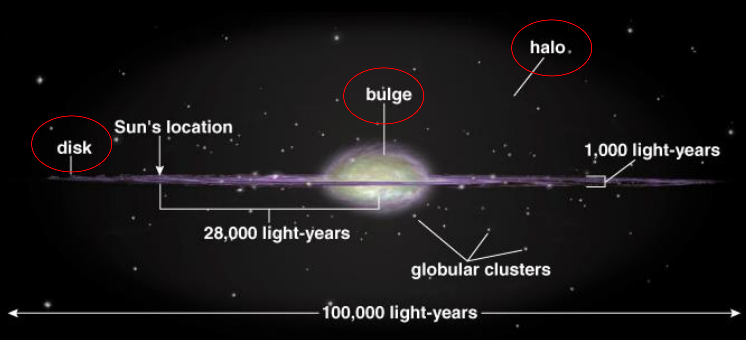
A Modern Map of the Milky Way

diameter of disk ~ 100,000 l.y. (30,000 pc)

radius of disk ~ 50,000 l.y. (15,000 pc)

thickness of disk ~ 1,000 l.y. (300 pc)

number of stars ~ 200 billion



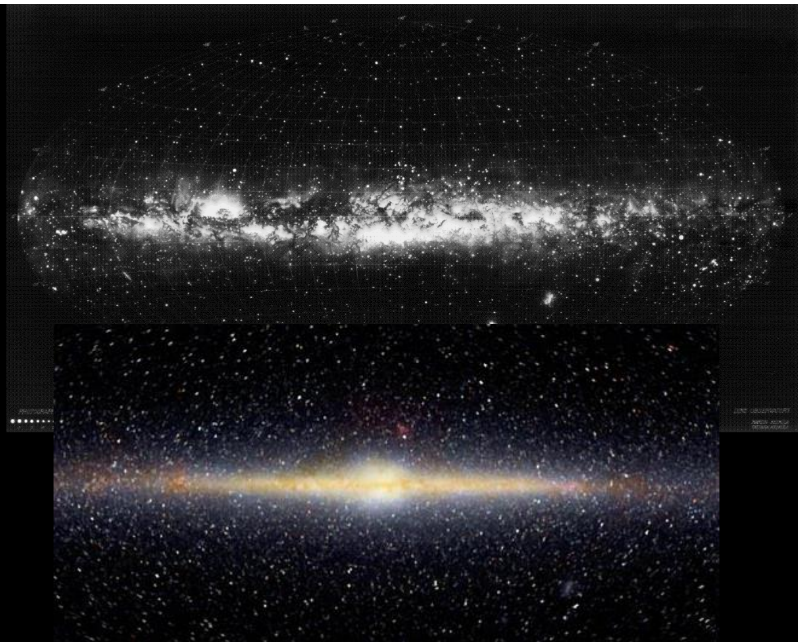
Important differences between these sub-regions:

1) Distribution of the ISM and star formation.

Roughly half of the visible matter in our galaxy appears to be in stars, and the other half makes up the Interstellar Medium (ISM) – the gas, dust, and other bits of matter between the stars in the ***disk*** and ***bulge*** of the Milky Way.

This ISM is mostly a vacuum (1 atom cm^{-3}), composed of about 90% gas (mostly H and He) and about 10% dust grains from heavier elements (primarily C and H compounds).

The ISM effectively absorbs and scatters visible light, and as a result it masks most of the Milky Way from our eyes. Radio & infrared light, however, passes through much of the ISM and allows us to study and map the Galaxy by making observations at these wavelengths (such as in the IR view shown above).



The ISM in our Galaxy also emits radiation, with the kind depending on what stage of the *star–gas–star cycle* it is in.

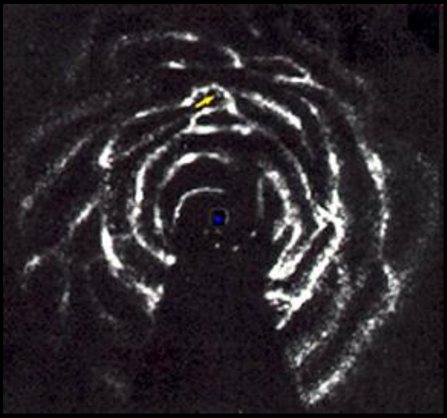
Recall that stars form heavy elements via fusion processes, and return these elements back into the ISM mostly via stellar winds during their post-main sequence “giant” phases – and, of course, when they violently go supernova, or more quietly form a planetary nebula.

Supernovae in particular eject high-speed gas and intense radiation into the surrounding ISM, carving out enormous “bubbles” of hot gas.

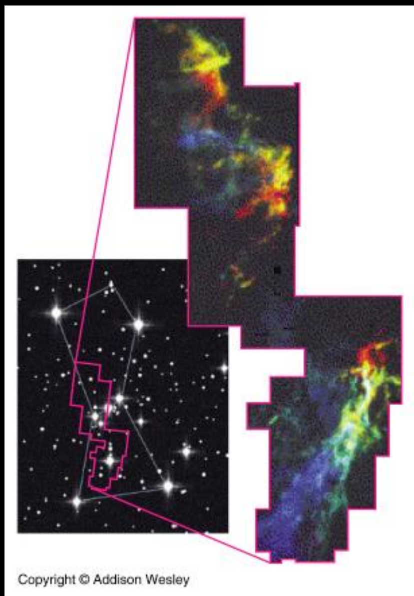
At temperatures > 10^6 K, the gas is ionized and emits X-rays. These hot bubbles fill 20–50% of the Milky Way’s disk.

However, because the ISM is so thick, these bubbles eventually stop expanding and the gas within cools, allowing ionized Hydrogen to recombine with electrons to form “atomic” Hydrogen.

The Milky Way contains some 5 billion $M_{\odot}$ of atomic Hydrogen, in large, warm (10,000 K) clouds that cool into smaller, denser clouds with temperatures around 100 K.



A map of the distribution of atomic H in the disk of the Milky Way; yellow arrow indicates the position of the Sun, blue dot indicates the Galactic Center.

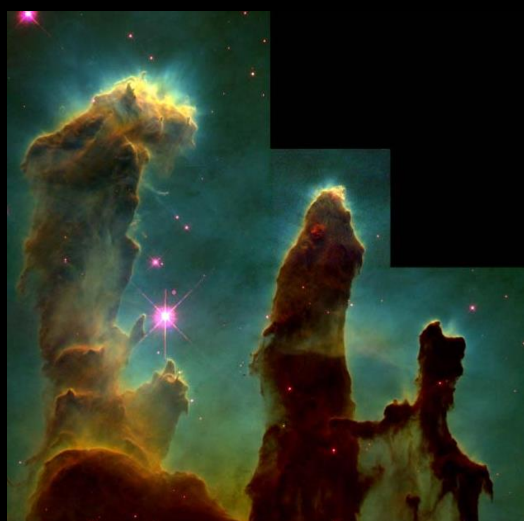


As atomic Hydrogen cools further to 10 – 30 K, it forms ***molecular Hydrogen*** (H_2). In these "molecular clouds", radio emission lines for many other molecules can be observed, including H_2O, CO, NH_3, OH, and other complex forms.

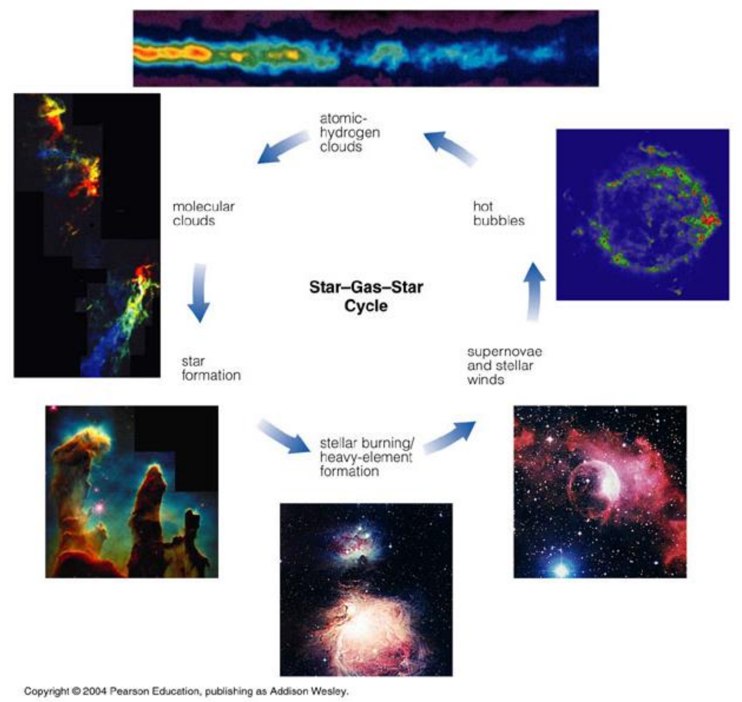
As gravitational forces increase, they can eventually trigger the formation of even denser cloud cores…

…and these cores can collapse into protostars!

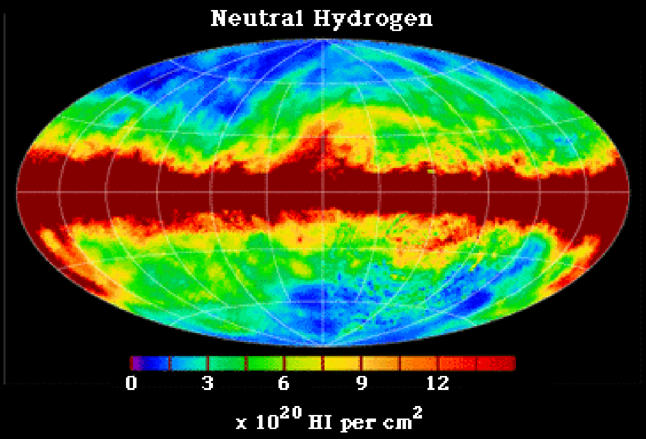
The whole star formation process begins anew, until after several tens of millions of years, the majority of the molecular cloud is eroded away by newly formed stars.



Eagle Nebula's "Pillars of Creation"



The Cosmic Circle of Chemical Processing – how zen is that?



However, star formation only occurs in significant amounts in the ***disk*** and ***bulge*** of our galaxy, because that's where the ISM is concentrated – there is very little ISM in the ***halo***, and so there's effectively no star formation there either.

The star-gas-star cycle is closely related to another important difference between the Milky Way’s major sub-regions:

2) Different Ages and Chemical Composition of the Stellar Populations:

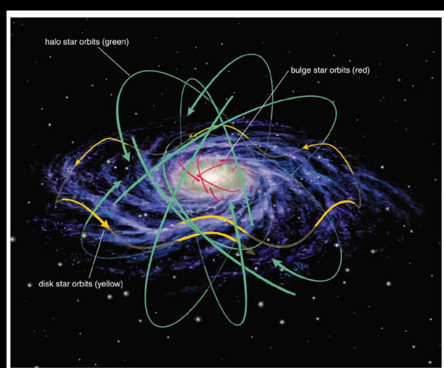
In the ***disk*** and ***bulge*** we see a mix of old and young stars, because stars continue to form in those regions. Further, the high-mass stars there cause the fraction of heavy elements in newly formed stars to steadily increase over time.

Stars in the ***halo***, however, are generally old, low-mass, red stars – and because there are no new high-mass stars forming (and haven’t been for a long time), the fraction of heavy elements in halo stars is much lower than in the disk or bulge.

A final important difference between these sub-regions:

3) Stellar Orbits in the Galaxy

Stars in the ***bulge*** and ***halo*** all orbit the Galactic center, but in randomly distributed directions and inclinations relative to the ***disk***, and with much higher average velocities than stars in the Milky Way’s disk.



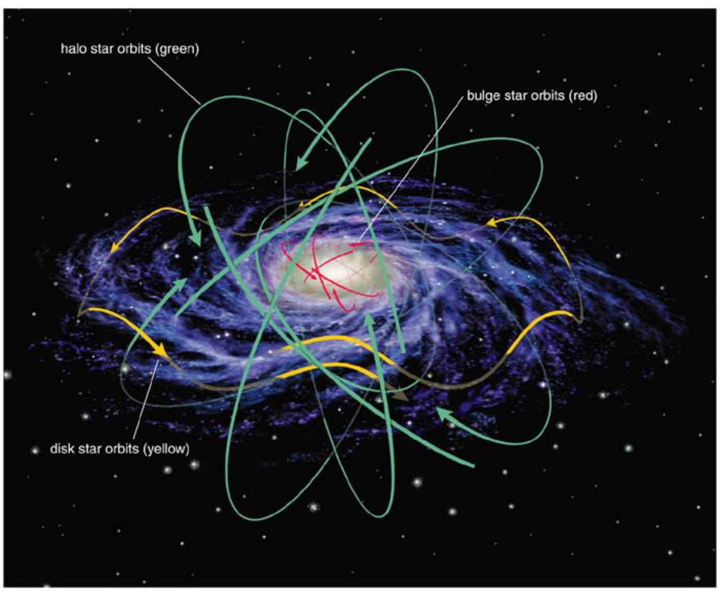
A final important difference between these sub-regions:

3) Stellar Orbits in the Galaxy

Stars in the ***disk*** also orbit the Galactic center, but in the same direction and in roughly the same plane (much like the planets in our solar system). They do “bobble” up and down quite a bit though, because of:

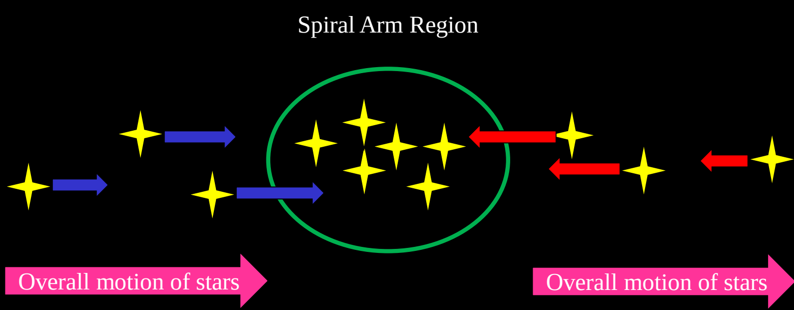
- the gravitational pull from nearby objects, and
- the combined pull of the entire disk.

This produces variations in their vertical velocities, and gives the disk its ‘thickness’.



M 51 – a decent approximation of the Milky Way's spiral arms

Similar gravitational effects produce the disk's spiral arms. These arms are <u>not</u> fixed strings of stars, revolving like the blades of a fan. The overall wave revolves at a different speed – and often in a different direction – than individual stars orbiting the Galactic center



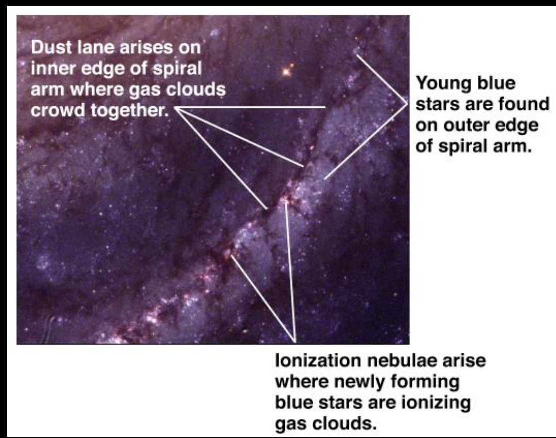
Star entering the arm are drawn in by the arm's gravity (blue arrows)…

…and then are slowed down by the arm's gravity as they leave (red arrows).

Spiral arms are caused by regions of slightly higher density, propagating around the disk. The waves sustain themselves by increasing the density of stars and ISM within their "crests".

The compression caused by density waves triggers the collapse of molecular clouds and star formation.

Short-lived O & B stars delineate the arms and make them blue & bright, while long-lived low-mass stars pass in and out of spiral arms in their orbits around the disk

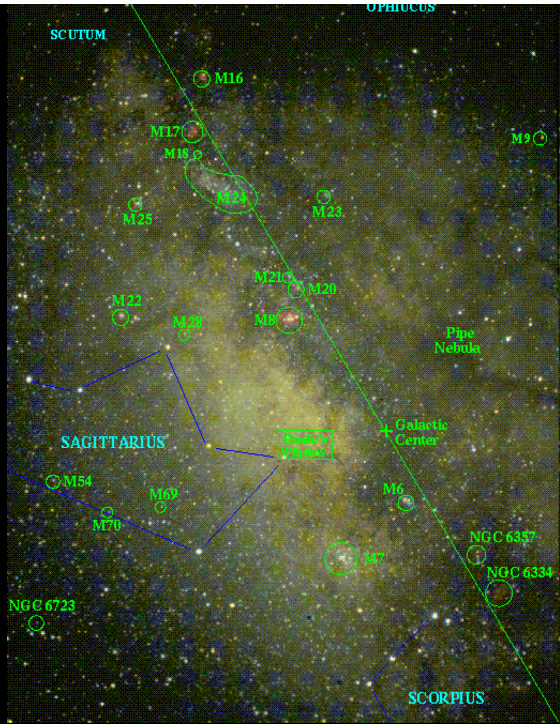


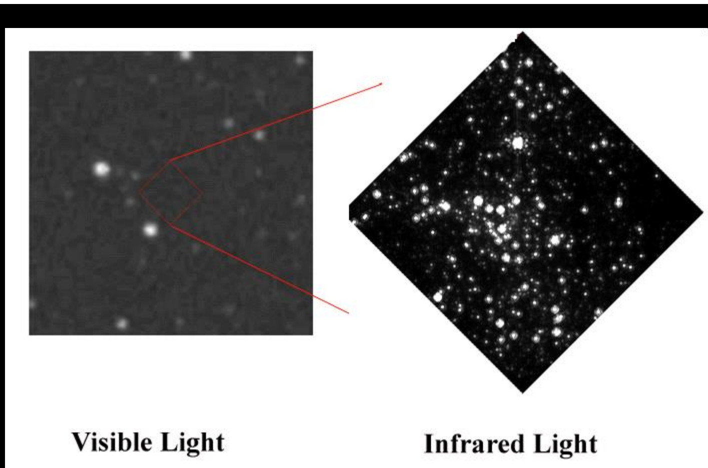
Planetary system – mass concentrated extremely heavily towards the center.

Galactic system – mass distributed much more broadly throughout.

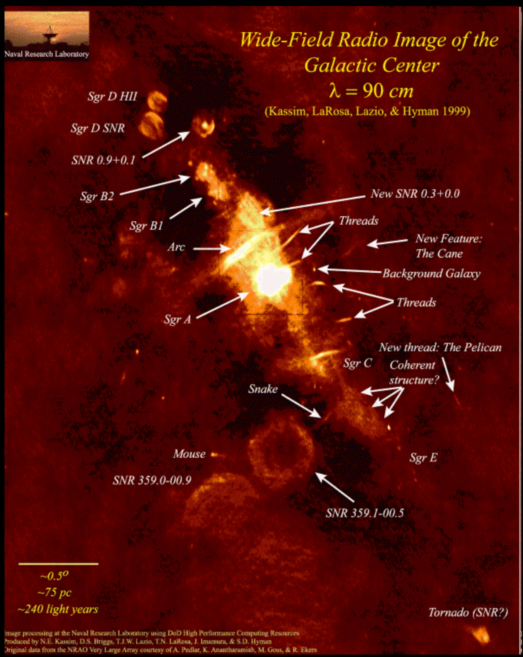
Stars orbit the center of the galaxy because that's where the *center of mass* of the ***entire*** Milky Way galaxy lies – ***not*** because there is some dominant object in the center that we are all orbiting around (like the Earth's motion is almost entirely driven by the Sun).

However, there **is** something strange going on in the galactic center, which we see from Earth in the direction of *Sagittarius*…

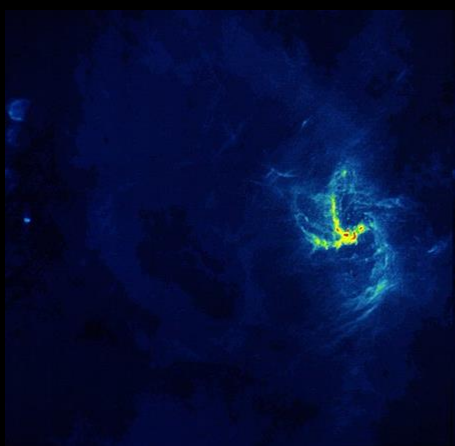




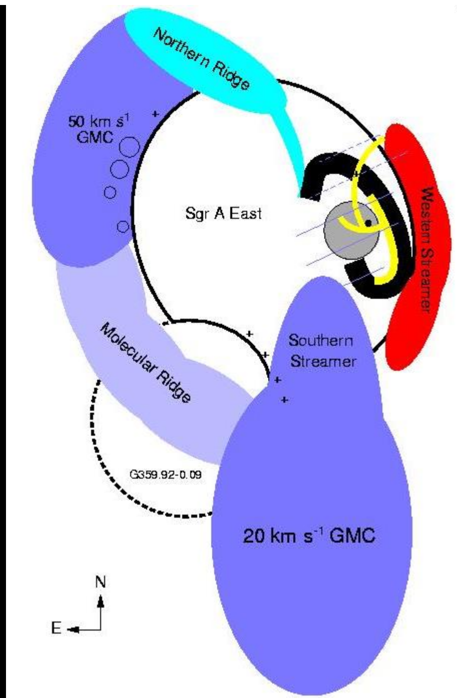
The region near the galactic center is highly obscured from us in the optical (seen on the left) by the concentration of ISM near the mid-plane of the Milky Way. However, infrared radiation (inset, image on right) easily penetrates this gas and dust.

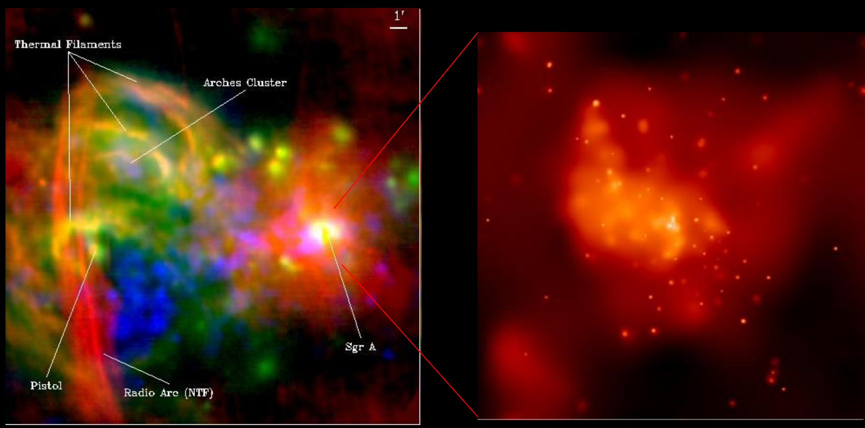


Radio wavelengths can also be used to image the Galactic center, and reveal it to be a very active location indeed, with an especially bright source at the location marked Sgr A. Note the size scales, both in terms of the angular size and true geometry at a distance of ~ 8kpc.



Zooming on the ~ 10pc square region centered on Sgr A, we see several very unusual molecular gas formations.

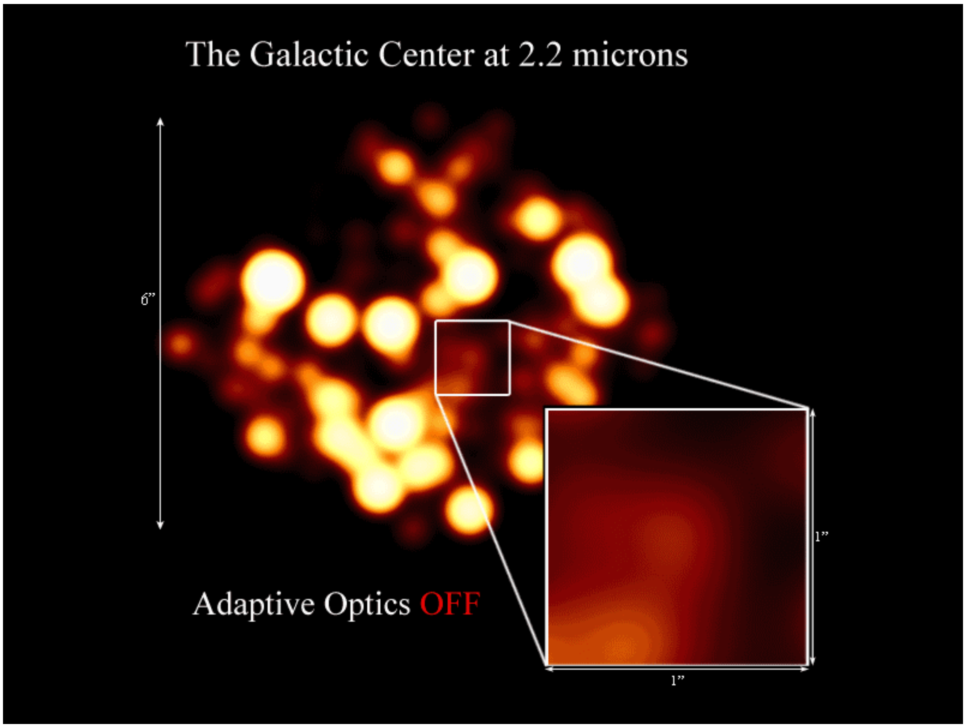


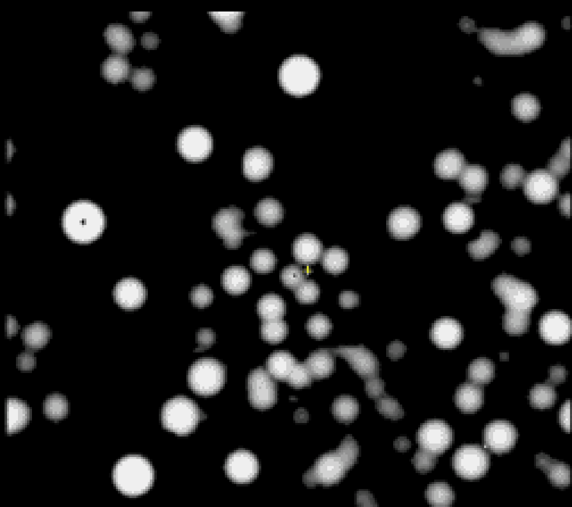


X-ray images from Chandra also reveal a very active region near the location of Sgr A, including many supernova remnants, and an unusually bright source near the center of the “mini-spiral” of gas seen in the previous radio images, named Sgr A*.

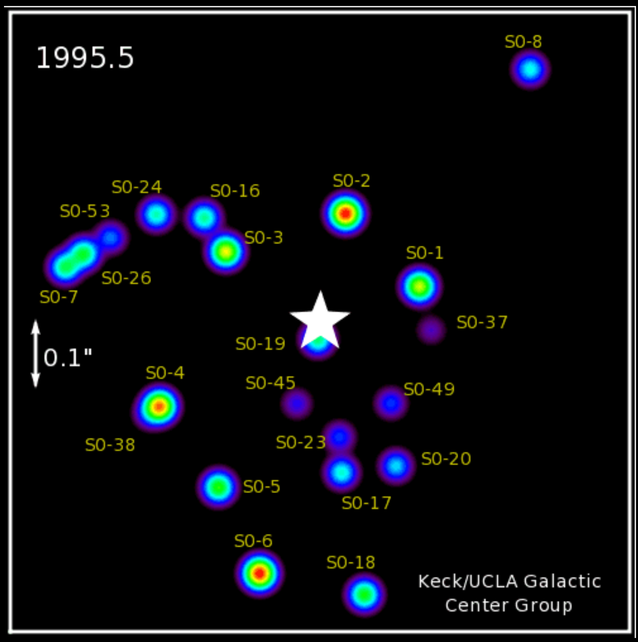
The twin 10m Keck telescopes, showing the laser used to produces a ‘guide star’ for ***adaptive optics***.

To try to understand what’s going on we have turned the most powerful telescopes and optical systems in the world on this tiny region.

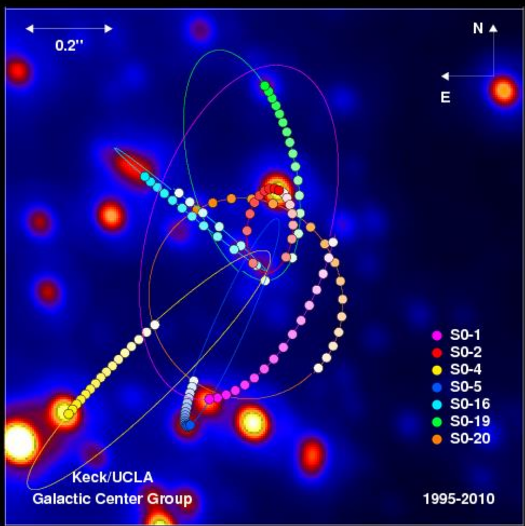


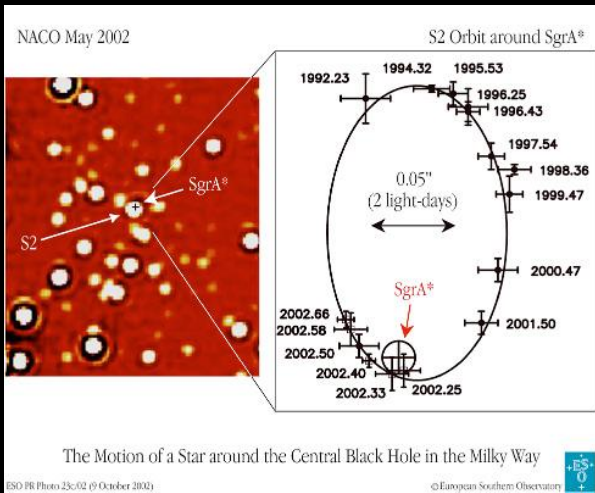


Much to our surprise, we’ve found that at the region coincident with Sgr A* lies a dark object with an enormous gravitational field – causing these stars to orbit the point marked with a cross in this image.



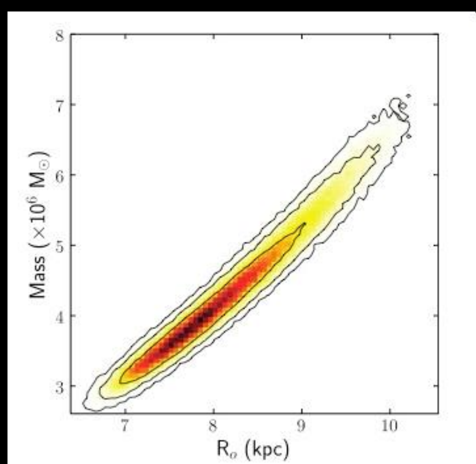
By tracing the orbits of these stars over time – a remarkable enough feat! – we can determine the mass of the central object that they are being gravitationally influenced by. This work has been largely led by a group at UCLA led by Andrea Ghez.

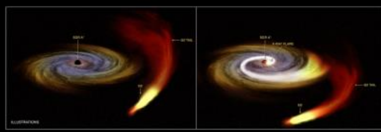


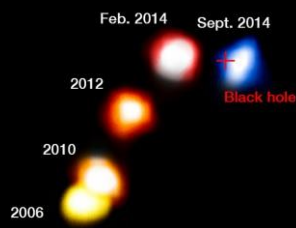


Star S0-2 has made one of the closest and most well-studied passes of Sgr A*, coming within 90 AU and reaching a top speed of over 4000 km/s – more than 1% of the speed of light!

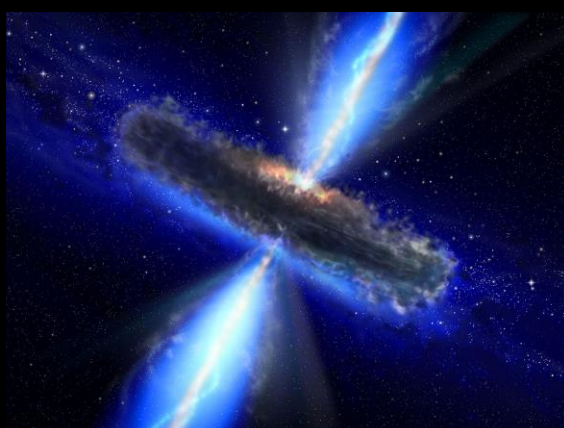
In order to accelerate stars to such speeds, the region around Sgr A* must contain a mass over 3 x 10^6 $M_{\odot}$. This object is a ***supermassive black hole*** – a very different sort of beast from the ***stellar mass black holes*** we have seen that form from the supernovae of high-mass stars.







The Schwarzschild radius of this enormous black hole would be over 3 million km across, meaning much lower tidal forces near the event horizon – and that's less than 0.3 AU, so you can get mighty close to it (~1 AU) before you'd get drawn in!



An artist's impression of a supermassive black hole with an accompanying accretion disk.

How did such an enormous black hole form? That question remains under vigorous debate, and the answer is highly uncertain. However it happens, though, it can't be too difficult – as we'll discuss in the coming weeks, we see such supermassive black holes in the hearts of almost every large galaxy!

Stay tuned as we begin to study these other galaxies – but before we do that, let's take a look at another important element of our own Galaxy – us!

Skip forward in your text to read Chapter 30 for next time, and come ready to talk about aliens and life in the Milky Way next time!