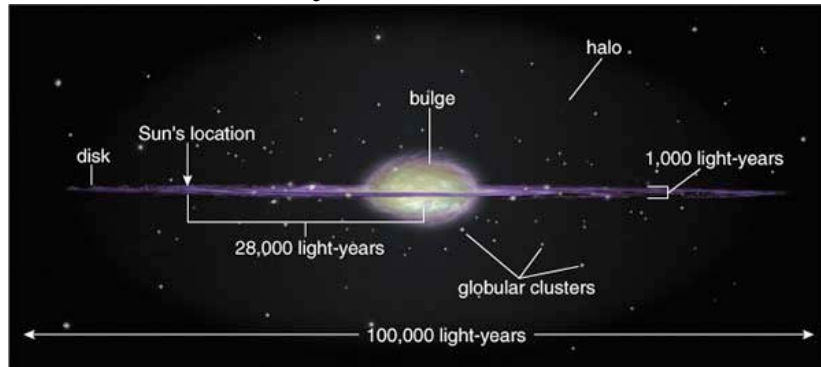


How Many Stars in the MW?



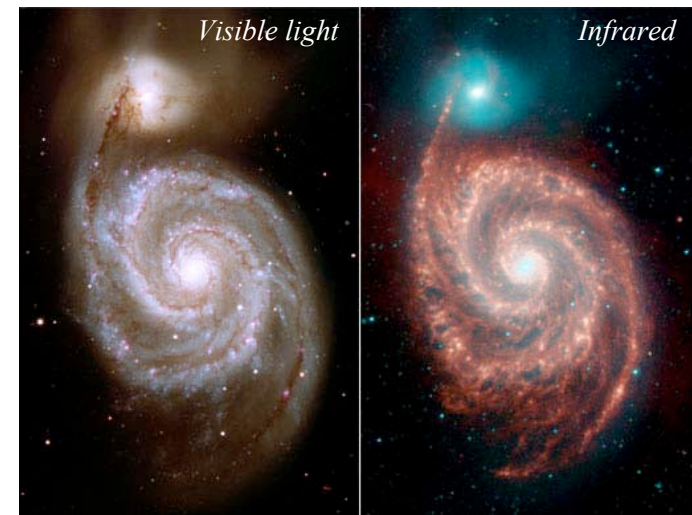
- ~100 billion stars!
- Half of **visible** mass is in the disk
 - Average separation between stars is about 5 light years
- The rest is in the bulge and halo.
 - Density of the bulge is millions of times larger than the disk.

Rotation of the MW

- Immanuel Kant (18th century) was right: **the MW has to rotate to balance gravity by centrifugal force.**
- The Sun is 28,000 light years away from the center of the MW, and orbits about the center at 220 km/s
 - About 1/1400 of the speed of light – fast rotation!
 - Balance between gravity and centrifugal force implies that mass *inside* the Sun's orbit is about **100 billion (10^{11}) solar masses.**
 - Fast rotation is necessary to balance large gravity.
- How about mass *outside* the Sun's orbit?
 - If there is no matter outside the Sun's orbit, then rotation speed decreases as $1/\sqrt{r}$
 - **Observations show that rotation speed remains the same beyond the Sun's orbit, even beyond the visible edge of the MW.**
 - Mass has to increase as r , but we don't see anything there...
 - Invisible mass → **Dark Matter**

“Pop” Stars in Galaxies

- Population I (*Pop-I*)
 - “Disk Stars”
 - Atmosphere contains 1-2% of heavy elements (heavier than He)
 - The Sun belongs to Pop-I
- Population II (*Pop-II*)
 - “Halo Stars”
 - Very little heavy elements
 - Old population
- Population III (*Pop-III*)
 - “First Stars”
 - No heavy elements
 - Primordial population
- Planet formation
 - which pop would be capable of having planets around?



ISM

- M51 (Whirlpool Galaxy)
 - Interstellar dust absorbs visible light and emits in infrared
 - These images tell us many things – Pay close attention to differences between two images.

Spiral Arms: Density Wave Theory

- Stars and spiral arms *do not* move together.
 - If they do, we have “winding problem”
 - The Sun orbits about the Galactic Center in 230 million years. In 10 billion years, it would orbit the G.C. 45 times.
- Spiral arms represent “density waves” propagating through the galaxy.
 - Waves do not carry stars or gas with them.
 - Very much like small waves in the sea. (not tsunami!)
 - When waves hit gas, density of gas increases.
 - In high density gas, stars are born.
 - The spiral arms appear to shine because of these newly born stars.
- Small mass stars (which look redder) escape from the arms, but high mass stars (which look bluer) don't.
 - Therefore, blue stars appear to follow the arms.

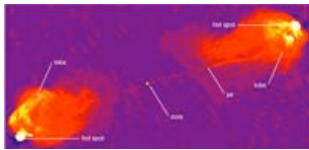
Central Black Holes

- It is believed that every galaxy hosts (at least) one black hole at the center.
 - Both spiral and elliptical galaxies host black holes.
 - Bigger galaxies host more massive black holes.
 - The black hole at the center of the MW weighs **3 to 4 million** solar masses.
- When black holes are *active*, they are called...
 - Active Galactic Nuclei (AGNs)
 - Quasars (QSOs)
 - The MW's central black hole is currently inactive.
- How did such giant black holes form?
 - We don't know.

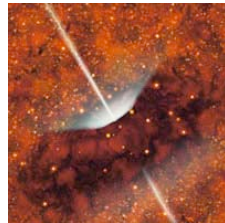
Active Galactic Nuclei



M87



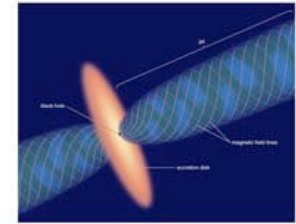
Cygnus A



(Artist's conception)

- AGNs were often called “QSOs (quasars)”, “radio galaxies”, or “Seyfert galaxies”, depending on how they look, for historical reasons.
- Very energetic sources, and luminosity varies in hours to days
 - This evidence suggests that AGNs are compact objects.
 - Black holes!

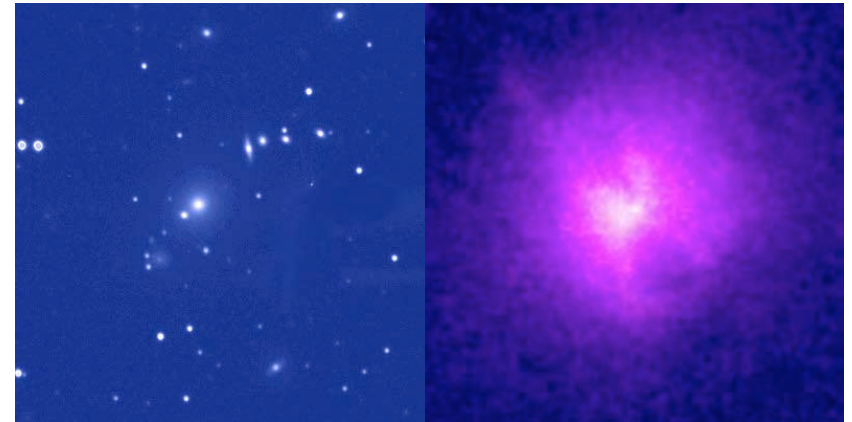
Emission Mechanism of Black Holes



- The primary source of energy for emission from black holes is *gravitational energy*.
- A black hole does not emit radiation, but the *accretion disk* surrounding it does emit.
 - As gas swirls down into the hole, it forms disk by conservation of angular momentum
 - Gas is heated by gravitational energy

Clusters of Galaxies

- Clusters of galaxies contain hundreds to thousands of galaxies
 - Each galaxy weighs about trillion solar masses.
 - Each cluster thus weighs about 100-1000 trillion solar masses.
- Lots of gas between galaxies within a cluster
 - About 17% of mass in a cluster is contained in gas.
 - About 3% is in stars in galaxies within a cluster.
 - The rest of mass is in dark matter.
- Large gravity is supported by gas pressure in Hydrostatic equilibrium
 - Gas temperature is about 100 million K
 - Hydrostatic equilibrium in the Sun gave 20 million K
 - Such a hot gas can emit in X-rays
- Clusters are “young”
 - Galaxies form first – galaxies then merge together to form clusters.



Visible Light

X-ray

Hydra A