The 65th Compton Lecture Series

The Quest for Gamma Rays: Exploring the Most Violent Places in the Universe

Lecture 5: Journey to the Center of the Galaxy

Elizabeth Hays
April 28, 2007

Slides and additional information can be found at *http://kicp.uchicago.edu/∼ehays*

1 Our Galaxy, the Milky Way

The Milky Way is one of billions of galaxies in our universe. The Solar System is embedded within it at 8 kiloparsecs [1] , or 26,000 light years, away from the center. Using the information about where stars and gas are located relative to us, we can infer what our Galaxy would look like to an outside observer.

Milky Way Facts [2]

- **Type:** Barred spiral galaxy. Most of the visible material is in a long narrow disk made up of spiral arms of stars and gas. At the center there is a bright bar-shaped region of stars. Around the center there is a sperical bulge of material. When we look towards the galactic center we see this as a widening of the plane of the galaxy. Additionally, the galaxy has a large spherical dark matter halo with a much lower density of visible objects.
- **Age:** 10 billion years plus or minus a few. We don't know this very accurately, but the oldest stars that have been found in the Milky Way are 13 billion years old[3].
- **Mass:** The galaxy as a whole has a mass of roughly 600 trillion Suns. This is distributed among a few hundred billion stars, but is dominated by the invisible dark matter permeating the galactic halo. We know this because we can measure the rotation of our galaxy using visible stars to determine how mass is distributed.
- **Size:** The galactic disk is about 100,000 light years in diameter and 1,000 light years thick. The halo extends out to around 180,000 light years.
- **Rotation:** Our solar system rotates around the center of the galaxy in about 230 million years.

---

[1] 7.94 ± 0.42 Eisenhauer et al. [2003]

[2] See any introductory astronomy textbook for more information about galaxy structure and evolution, e.g. Shu [1982] or Binney & Merrifield [1998].

[3] The age of the Universe is estimated by several different methods to be around 14 billion years.

- **Where are we?** The Solar System is about 8 kpc (26,000 light years) away from the center of the Galaxy in a small spiral arm called the Local or Orion Arm.

The Center of the Milky Way

The centers of galaxies can be complex and dense regions. In many cases we would like to know more about the centers of galaxies to determine how the galaxy formed and has evolved over time. One way to learn about other galaxies is to study the one nearest to us, our own Milky Way Galaxy. The gas and dust between us and the galactic center block visible light, but we can study it at radio, infrared, high energy X-ray, and gamma-ray wavelengths. What we have learned is that the center of our Galaxy is a complex region containing several types of celestial objects.

- **A supermassive black hole candidate, Sagittarius (Sgr) A^*** - Observations of the center of the Milky Way suggest that the very center is a black hole with a mass of about 2.6 million Suns. The radio source discovered here was named for the constellation that appears in this part of the sky, Sagittarius. The black hole accretes nearby material and may be generating strong winds and shocks that produce high energy photons.
- **A supernova remnant, Sagittarius A East** - Another radio source detected in the center of the galaxy is the shell remnant leftover from the blast wave of a supernova explosion.
- **Star clusters** - The inner few thousand light years of the galactic center contain a cluster of cool, mature stars. Within this cluster is a smaller cluster of young hot stars in the central few parsecs of the Galaxy. The young stars form a region of very strong winds by blowing off outer layers of hydrogen.
- **Clouds of molecules and ionized hydrogen** - A disk of molecules rotates around the small, young cluster of stars. Within this disk there is additionally a region of ionized gas that rotates around Sgr A^*.

The area containing Sgr A^* produces an extended very high energy gamma-ray source, but it is a challenge to discern which objects are playing a role in this signal. There are several hot regions that generate strong winds and shocks, and there are also several regions that provide target material for producing gamma rays. Additionally, the center of our galaxy is one of the places that we expect a higher density of dark matter. There are too many ways to generate gamma rays here, but further measurements at all wavelengths will help solve this puzzle. No matter what the source is, the galactic center offers a great opportunity to understand the core of a galaxy and how a central black hole influences the formation and development of the surrounding Galaxy.

2 Very High Energy Gamma-Ray Telescope Arrays

Most telescopes that look for very high energy gamma rays are *imaging atmospheric Cerenkov telescopes* [4] (IACTs). A moderately-sized, segmented optical reflector focuses light onto a fast, very sensitive camera. The camera records the visible light track through the sky from a particle air shower caused by a gamma ray after entering Earth's atmosphere. The light from the air shower is very faint; this is why you cannot see it with your eye. The big mirror and fast camera are necessary to pick out faint Cerenkov flashes against background light from the stars and any local light sources. The cameras are so sensitive that they cannot be used in daylight or even bright moonlight without being damaged. A few hundred Cerenkov flashes are recorded every second on dark, clear nights when the moon is not overhead. The telescopes only see a few degrees of sky at a time and have to be pointed at a part of the sky with a known or suspected gamma-ray source.

Why an array of telescopes instead of a single big telescope? [5]

IACTs are combined in pairs or fours to make an array covering an area about 100 meters across. The separation distance is determined by the extent of the Cerenkov light pool fon the ground. Two telescopes that are 80-100 meters apart are still close enough to see many of the same air showers. Why do we use more than one telescope to look at the same air shower? The goals is to select showers caused by gamma rays and reject accidental pictures of cosmic-ray showers or background light in the sky. We also want accurate knowledge of where the gamma ray came from in the sky to determine the celestial object producing the gamma rays.

1. **Avoid images of background light** - When an IACT sees enough light in a very small amount time, it records an image. Sometimes this will be a of a Čerenkov shower. However, other sources of light in the sky trick us into taking pictures without air showers. The visible light background includes things like star light, light from cities and developments, airplanes, satellites, meteors, end Čerenkov light from an energetic particle that reaches the ground and passes very close to the telescope. When enough of this background light hits our camera at the same time, we end up taking a picture that we cannot use. After we take the picture, we use the image shape to decide if it belongs to a Čerenkov shower or not, but we prefer to not take pictures that we will throw away. By using several telescopes together, and only taking a picture when two or more telescopes see a flash of light at the same time, we avoid wasting our time on background light from particles passing near one of the telescopes.

2. **Reject Čerenkov light caused by cosmic rays** - Many of the Čerenkov flashes that we record are caused by cosmic rays and not by gamma rays. In fact there are 1000 or more images of light caused by cosmic-ray air showers for every gamma-ray

---

[4] Weekes [2003] reviews very high energy telescopes.

[5] Hofmann et al. [1999] provides technical details of the advantages of studying Čerenkov air showers using multiple telescopes.

image that we record. It is hard to tell the difference, but the more information we have about the shower, the more likely that we can pick the pictures that are related to a gamma-ray source and throw away images of cosmic-ray air showers.

3. **Improve knowledge of gamma ray origin** - Taking pictures of the same Cerenkov shower with several telescopes provides views of the shower from different locations. This is a little like combining footage from cameras looking at the same object from different spots to make a 3-D movie. Multiple views give us a much better idea how a shower tracked down through the atmosphere. This tells us more accurately where the original gamma-ray came from in the sky. This means we can better determine the location of a gamma-ray source, and how big it appears in the sky. If the gamma-ray source is very large and bright, we can even look for spatial features.
4. **Improve knowledge of the energy of the initial gamma ray** - Multiple images of the same shower not only improve our knowledge of the origin of the gamma ray, but also improve how the accuracy on how far away the shower fell from our telescopes. That allows us to do a much better job of removing cosmic-ray-induced air showers from our data and keeping the gamma-ray showers that we do want. Better rejection of cosmic-ray showers improves the measurement of the energies of the initial gamma rays that hit the Earth's atmosphere.

References

Binney, J., & Merrifield, M. 1998, Galactic Astronomy, Princeton, NJ : Princeton University Press, 1998. (Princeton series in astrophysics)

Eisenhauer, F., Schödel, R., Genzel, R., Ott, T., Tecza, M., Abuter, R., Eckart, A., & Alexander, T. 2003, ApJ, 597, L121

Hofmann, W., Jung, I., Konopelko, A., Krawczynski, H., Lampeitl, H., Pühlhofer, G. 1999, Astroparticle Physics, 12, 135

Kosack, K., et al. 2004, ApJ, 608, L97

Melia, F., & Falcke, H. 2001, Annual Reviews of Astronomy and Astrophysics, 39, 309

Schödel, R., et al. 2002, Nature, 419, 694

Shu, F. H. 1982, A Series of Books in Astronomy, Mill Valley, CA: University Science Books, 1982,

Weekes, T. C. 2003, Very high energy gamma-ray astronomy, IoP Series in astronomy and astrophysics, Bristol, UK: The Institute of Physics Publishing, 2003

Yusef-Zadeh, F., Melia, F., & Wardle, M. 2000, Science, 287, 85