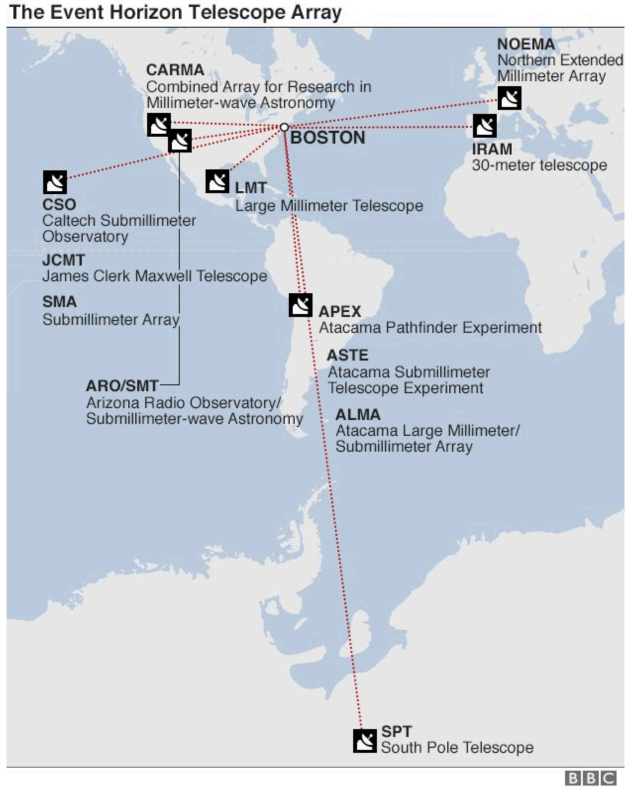
Astronomy Review and Explore

Picturing a Black Hole!



A team at MIT is using interferometry to attempt to create an image of black hole Sag A* at a wavelength of 1.3 mm. The goal is to achieve a resolution of 50 μas in order to glimpse the event horizon.

The EHT's trick is a technique called very long baseline array interferometry (VLBI). The EHT is aiming initially to get down to 50 microarcseconds. Team-members talk in analogies, describing the sharpness of vision as being the equivalent of seeing something the size of a grapefruit on the surface of the Moon.

Although never seen directly, this object, catalogued as Sagittarius A*, has been determined to exist from the way it influences the orbits of nearby stars. These race around a point in space at many thousands of km per second, suggesting the hole likely has a mass of about four million times that of the Sun. But as colossal as that sounds, the "edge" of the black hole - the horizon inside which an immense gravity field traps all light - may be no more than 20 million km or so across. And at a distance of 26,000 light-years from Earth, this makes Sagittarius A* a tiny pinprick on the sky.

BBC News 16 February 2017

1. All of the participating telescopes observed Sag A* on the same date and stored about 500 terabytes of information on special hard drives that were shipped to MIT for analysis by supercomputer to produce a single image! How does this story illustrate the way that interferometry works?
2. Determine the frequency of the observed 1.3 mm radiation. What type of EMR is it?
3. Given the event horizon size 20 million km and the distance 26000 light years determine the approximate angular diameter of the “hole” in microarcseconds.
4. Determine the diffraction limit of the interferometer network given the separation of the telescopes is approximately 10 000 km.
5. According to the theories about stellar evolution some stars are so massive that when their energy is exhausted they form black holes. At what minimum mass star does this happen?
6. Sagittarius A* is clearly well beyond the minimum mass. In fact it is so far beyond one might ask is there ever a single star with that much mass that could form this black hole? If not, then how did such a black hole form in the first place?

Orbits of Stars About Sagittarius A*

The diagram shows the orbits of several stars about an unseen dark object located at the center of our Milky Way galaxy. The only known explanation for these orbits is that there must be a very massive and yet dark object at the location of the dot shown at the origin.

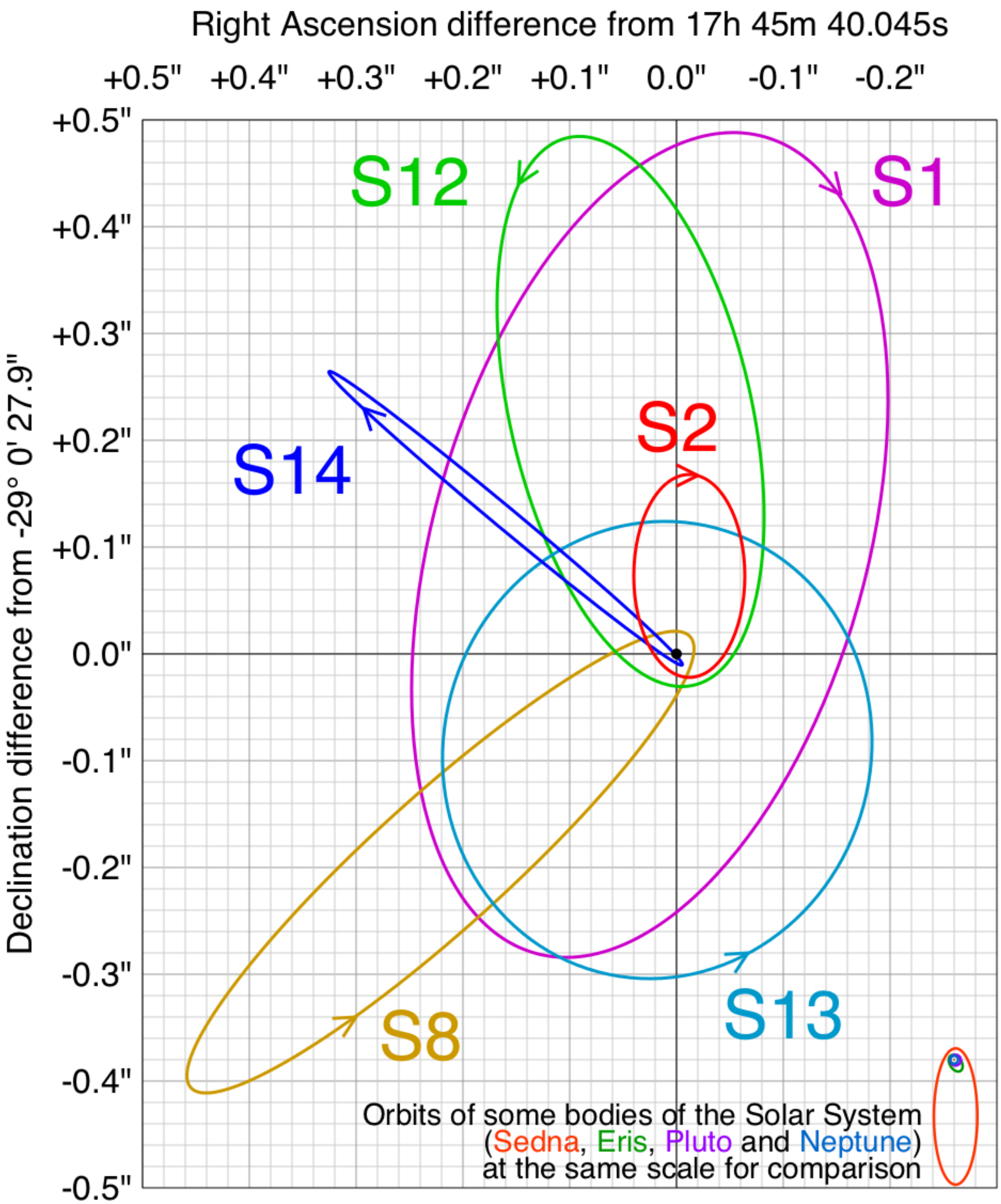
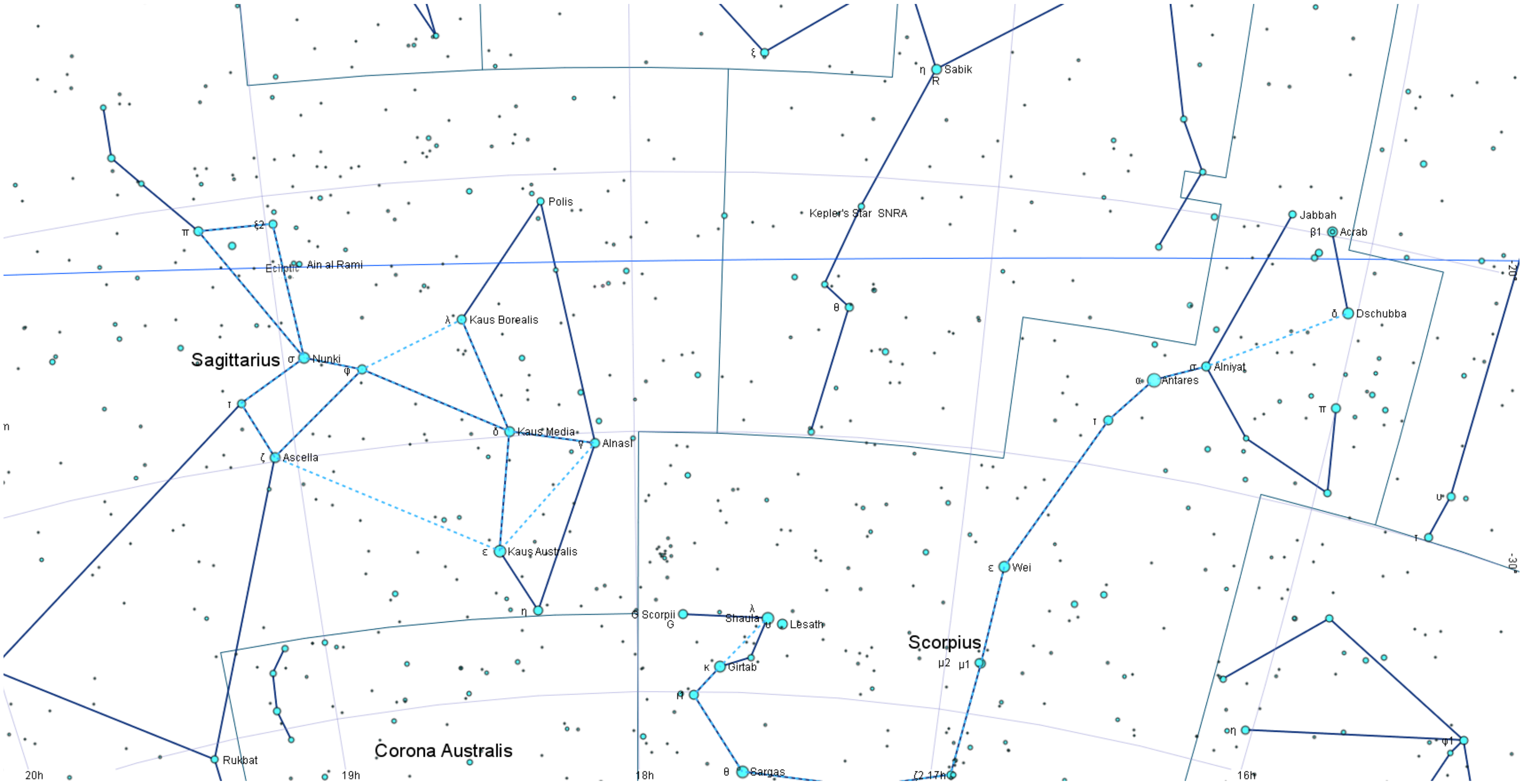


diagram: Cmglee, Wikipedia


Sagittarius
Scorpius
Corona Australis
Nunki
Ascella
Kaus Borealis
Kaus Media
Kaus Australis
Alnasl
Polis
Ain al Rami
Ecliptic
Rukbat
Sabik
Kepler's Star SNRA
Antares
Alniyat
Jabbah
Acrab
Dschubba
Wei
Shaula
Lesath
Girtab
Sargas
Scorpii
20h
19h
18h
17h
16h
-20
-30

Questions Based on Orbit Diagram and Sky Chart

1. Notice the labels on the *x*-axis and *y*-axis. (a) The origin of this graph represents Sagittarius A* – it is located at what celestial coordinates? (b) Use the coordinates to find this position on the star map below and confirm the constellation in which it resides. It is actually very near borders with two other constellations – which ones? (c) What asterism would be quite handy for locating Sagittarius A*? (d) Notice the proximity to the ecliptic – this means that periodically it would be difficult for astronomers to observe Sagittarius A* – when and because of what object? (e) Also, Sagittarius A* happens to be quite near the most southerly point on the ecliptic – a special point called what? (f) Which of the stars in the orbit diagram would come closest to the ecliptic and what would be its declination when it does? (g) Which of the stars in the orbit diagram would come closest to the star Alnasl and what would be its right ascension when it does?
2. Look carefully at the diagram and consider Kepler's 1st Law of Planetary Motion. Considering that the small dot at the origin represents the supermassive black hole, which orbits appear to follow Kepler's 1st Law and which ones do not? Why do you think some of the orbits appear to contradict the law?
3. The orbital diagrams shown in the figure are the paths followed by stars as viewed from Earth and "mapped" on the Celestial Sphere. If the orbit of a star is tilted relative to the map then its true shape will not be shown. (For example, a circular orbit would look like an ellipse if viewed at an angle.) Not apparent in the diagram is any motion of a star either toward Earth or away from Earth. What is this type of motion called? How could it be determined (by the diagram or by any other method)?
4. Using a ruler, or simply using the grid of squares, determine the eccentricity of S8 and of S13.
5. Determine the greatest distance of S8 from the black hole in units of arcseconds and in astronomical units. What would this distance be called?
6. Given that the period of S13 is 36 years, use Kepler's 3rd Law to determine the period of S8 and of S2. Compare your calculated values to published values of 67 yrs and 15 yrs. Why are there discrepancies?
7. Look at the comparison diagram showing some orbits of solar system objects at the same distance scale as the star orbits. Given that Neptune takes 165 years to orbit the Sun and Pluto takes 248 years to orbit the Sun what must be true of the black hole in order to explain that the orbit of S2 is only about 15 years? (Ask yourself – if S2 were orbiting the Sun instead, how long would it take? Or if Pluto were orbiting the black hole instead, how long would it take?)
8. Optional challenge: Newton's modified version of Kepler's 3rd Law is $P^2 = a^3/(M_{total})$ in solar units. Use the comparison diagram of Sedna's orbit, P = 11400 yrs (the largest one) to determine the approximate mass of the black hole in solar units.

Answers to 1st set (based on BBC story):

1. Interferometry combines light or other EMR from separate telescopes, and interference of the waves yields increased resolution limited by the "synthetic aperture" equal to the separation of the telescopes.
2. 230 GHz microwave/radio
3. 17 μas
4. 33 μas
5. Stars of mass 12 times that of the Sun or greater are expected to form a black hole when they run out of energy and the core collapses.
6. Astronomers do not think that a "supermassive" black hole like Sagittarius A* formed from the collapse of a single star. In fact it is not actually known with certainty how it formed. However, one possibility is that it is the result of many smaller black holes merging to form one big one. Recent observations of gravity waves by LIGO provide evidence of black holes merging.

Answers to 2nd set (based on star chart and orbit diagrams):

1. a. $17^h\ 45^m\ 40.045^s$, –29° 00′ 27.9″
   b. It is located in Sagittarius near the borders with Ophiuchus and Scorpius.
   c. The "teapot" of Sagittarius would seem to "pour" into the black hole!
   d. The Sun would lie between observers on Earth and Sagittarius A* in the month of December and this makes it hard to observe at that time.
   e. The most southerly point on the ecliptic at 18h is called the Winter Solstice and the Sun would be there on December 21 +/- a day.
   f. S1, –29° 00′ 27.5″
   g. S8, $17^h\ 45^m\ 40.076^s$
2. Do not appear to follow Kepler's 1st law: S1, S2, S12, S14
   Do appear to follow Kepler's 1st Law: S8, S13
   By the 1st Law the black hole should be located at one focus on the major axis of the ellipse. The orbits for which this does not appear possible must be oriented in a plane that is not perpendicular to our line of sight, causing it to look skewed.
3. Motion toward or away from the Earth is called radial velocity and it may be determined by blueshift or redshift in the star's spectrum.
4. S8 $e = 0.94$; S13 $e = 0.43$
5. S8 greatest distance 0.613″ or 4880 A.U. – this is called "apoastron" (not aphelion).
6. S8 $p = 63$ yrs; S2 $p = 11$ yrs – Any discrepancies are likely due to error measuring the values. Also, Kepler's 3rd Law ignores the effect of mass on period, but this effect is smaller when the mass of the object in orbit is less than the object being orbited. In this particular case the mass of any of the stars orbiting the black hole is much, much, much, much, much, less than the mass of the black hole. So that should not be a problem here!
7. If S2 were orbiting the Sun instead of the black hole it would take 1000's of years to orbit instead of 15 years. If Pluto were orbiting the black hole instead of the Sun it would take less than a year to orbit instead of 248 years. This means that the black hole has to have a much stronger gravitational field than the Sun and therefore it must be many times more massive than the Sun.
8. The mass of the black hole is about 4 million times the mass of the Sun.