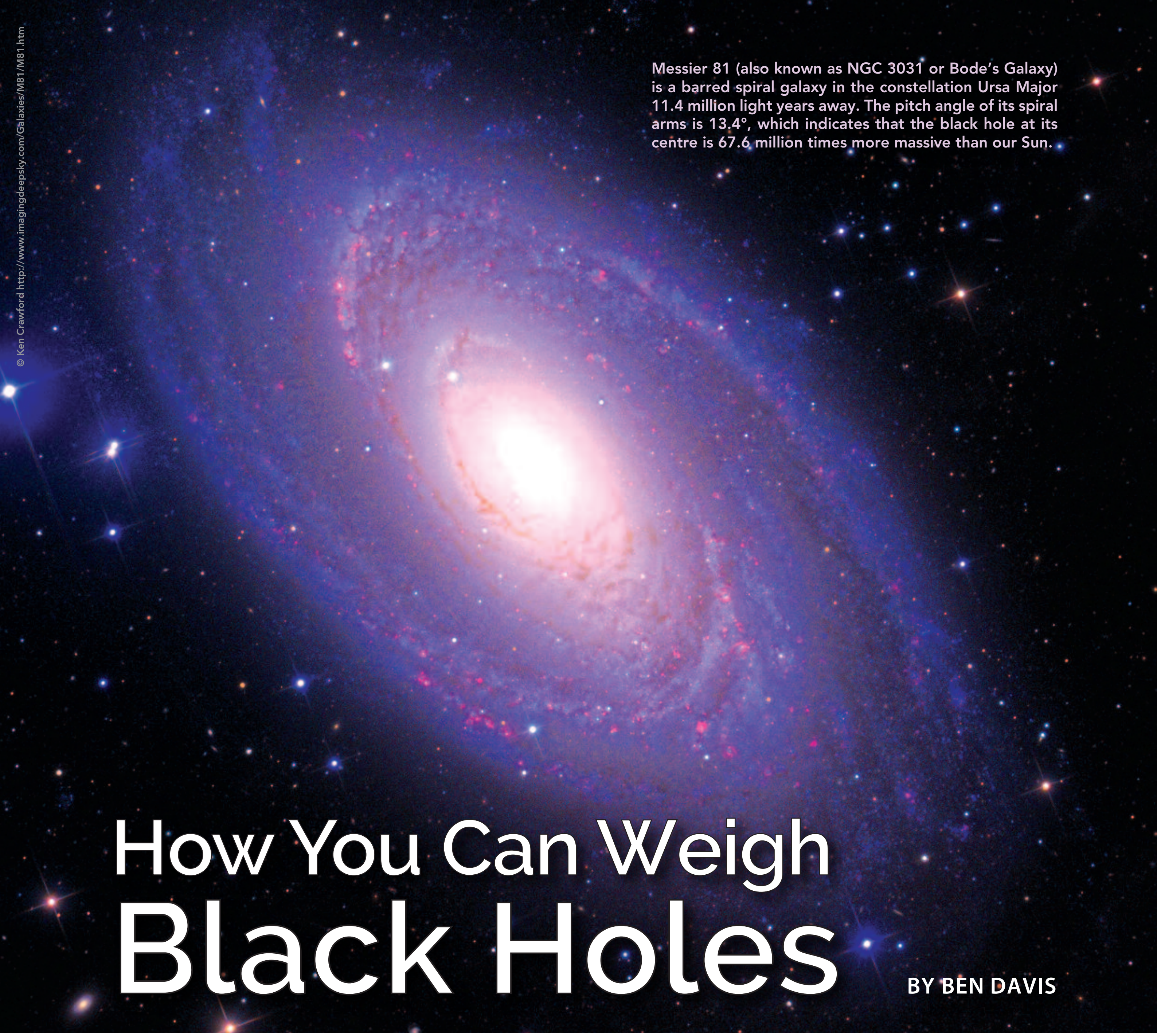


Messier 81 (also known as NGC 3031 or Bode's Galaxy) is a barred spiral galaxy in the constellation Ursa Major 11.4 million light years away. The pitch angle of its spiral arms is 13.4°, which indicates that the black hole at its centre is 67.6 million times more massive than our Sun.

How You Can Weigh Black Holes

BY BEN DAVIS

The largest invisible monsters in our universe are hidden at the centres of galaxies, and we can predict how massive they are by the shape of spiral arms in their host galaxies. Here's how you can take part in a global "citizen science" census of black holes.

Nearly a century ago, Sir James Jeans and Edwin Hubble noted that spiral galaxies with large central bulges possess tightly-wound spiral arms, while spiral galaxies with small bulges display wide-open spiral arms. Their studies have defined the classification scheme of galaxies famously represented in the "tuning fork" diagram (Fig. 1).

For nearly 100 years, astronomers have been classifying spiral galaxies by eye and denoting their "Hubble type", with the tightness of winding of spiral arms denoted by a lowercase letter (e.g. "Sa" for galaxies with large bulges and tightly-wound spiral arms). This is a qualitative description of the winding rate of spiral galaxies, and is a bit like labelling automobiles into a few descriptive categories according to their fuel economy: efficient, mediocre and gas-guzzler. It is a helpful description, but before you invest thousands of dollars in a vehicle you might want to know the specific measurement of a vehicle's average fuel economy in some quantifiable unit like kilometres per litre.

For spiral galaxies, this quantifiable unit is the logarithmic spiral "pitch angle" (Fig. 2), which allows us to measure the tightness of spiral arms in galaxies in units of degrees. The range of possible pitch angles is between 0° (a spiral so tight that it has become a circle) and 90° (a spiral so loose that it has become a straight line).

Just as knowing accurate estimates for your car's fuel economy can help you adequately calculate fuel expenses for your vehicle, knowing the shape of spiral arms accurately can help astronomers estimate properties of the galaxy, notably the mass of the black hole lurking at its centre.

For the past couple decades, astronomers have been very interested in so-called "supermassive" black holes. These black holes are not the typical variety of black holes resulting from the death of stars that are a few times more massive than our Sun. These behemoths have accumulated their great mass – millions or billions of times the mass of our Sun – from billions of years of consuming material that has ventured close enough to fall in or from violent collisions with other supermassive black holes. In the latter case, their mass increases rapidly and radiates away large amounts of gravitational waves.

Supermassive black holes are now widely studied because they are now thought to reside at the centre of nearly all galaxies. Together, galaxies and their companion supermassive black holes have evolved together over the course of billions of years. Because of this, they can help us study the evolutionary history of galaxies.

Many fundamental questions still exist, including a version of the "chicken vs the egg" dilemma: which came first, the supermassive black hole or the galaxy? Regardless of the answer, it is apparent to astronomers that there is feedback between the two, with the environment in galaxies dictating how quickly a supermassive black hole can grow and the size of the black hole in turn affecting the geometry of spiral arms of the galaxy.

Our recent study, published in the *Monthly Notices of the Royal Astronomical Society* (https://arxiv.org/abs/1707.04001), has found that the shape of spiral arms is a strong indicator of the mass of the supermassive black hole at the centre of a galaxy. Massive black holes exist in galaxies with tightly-wound spiral arms, and less massive black holes exist in galaxies with loosely-wound spiral arms.

The template in Figure 3 is an accurate representation of the true shape of spiral arms in galaxies and the mass of their associated black hole. This connection is essentially an intuitive one that links the different regions of a galaxy: the nucleus, bulge and disc. A very large black hole (residing in the nucleus) lives within a very large bulge and vice versa. These contribute to the overall gravitational potential well of the galaxy, which further influences the motion of matter in the disc of a galaxy.

Thus, deeper gravitational potential wells coerce matter to spiral tightly around the centre and vice versa. This allows anyone, not just professional astronomers, to simply look at a spiral galaxy and immediately estimate the mass of its central black hole.

Watching things go around other things is how astronomers have "weighed" celestial objects for centuries. After all, how does one weigh the Earth? You can watch the Moon. The speed at which the Moon orbits the Earth is proportional to the mass of the Earth. If the Earth was more massive, the Moon would orbit more quickly (the month would be shorter) and vice versa.

By knowing the Moon's orbital period, the distance between the Earth and Moon, and applying Isaac Newton's Universal Law of Gravitation we can calculate the mass of the Earth. This is how all astronomical objects are weighed.

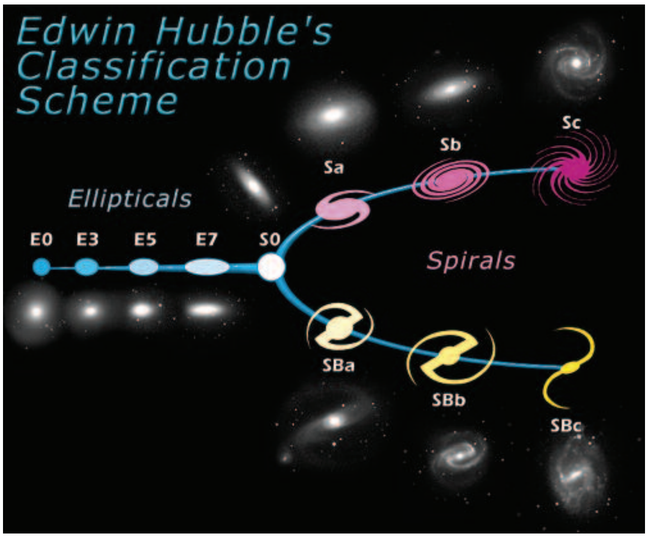


Figure 1. The "tuning fork" diagram of galaxy morphology. Credit: NASA & ESA

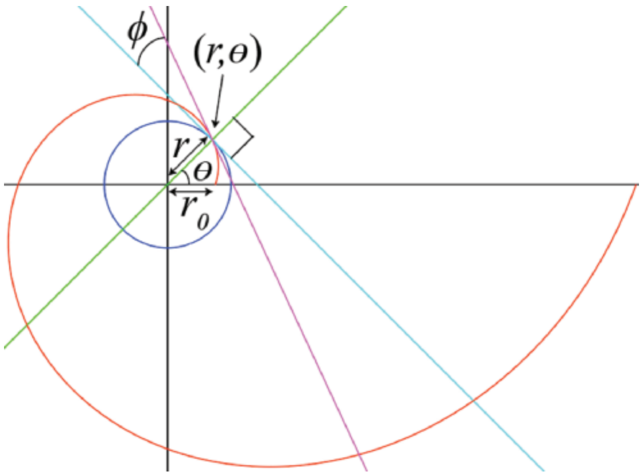


Figure 2. The pitch angle (φ) defined geometrically. Credit: Benjamin Davis

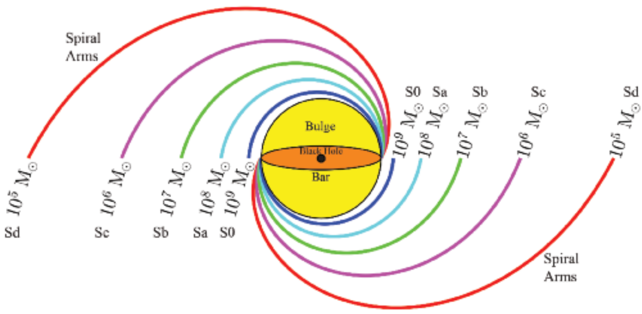
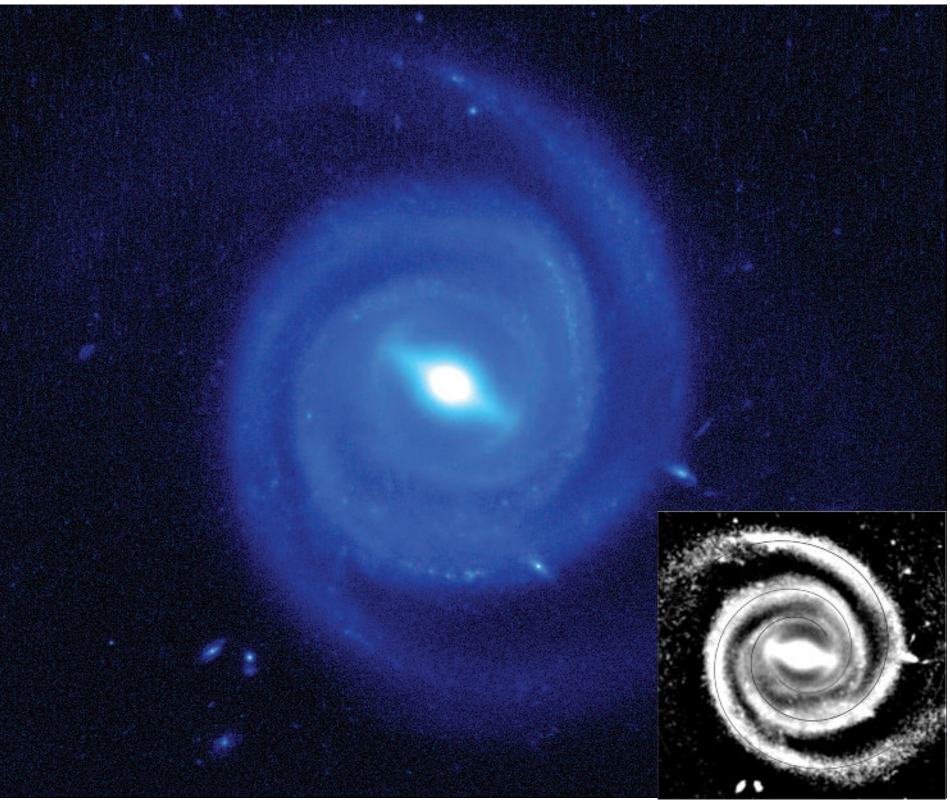


Figure 3. Spiral galaxy arms with varying degrees of tightness, and the corresponding galaxy type and central black hole mass in units of our Sun's mass. This template can be used to estimate the black hole masses in spiral galaxies. Credit: Benjamin Davis

"… you can become a census collector helping us determine the demographics of all the black holes residing in all of the spiral galaxies throughout the universe.



UGC 6093 is a barred spiral galaxy 535 million light years away. Inset: The galaxy is overlaid with logarithmic spirals with a 10.2° pitch angle, indicating that its black hole is 28.2 million times more massive than our Sun.

This is easy for objects that have natural satellites orbiting them, like the Moon orbiting the Earth, but if there are no natural satellites we need to send our own satellites there to orbit them and thus determine their mass. In the case of the Moon, humanity did not accurately know its mass until we sent spacecraft to orbit it.

Since we cannot yet send spacecraft to orbit distant supermassive black holes at the centre of other galaxies, astronomers must look for (and hopefully find) material orbiting these black holes in order to weigh them. The supermassive black hole at the centre of our Milky Way is close enough to enable astronomers to watch individual stars orbit the black hole. These stars have been closely watched for decades, and allow us to accurately measure its mass to be approximately four million times more massive than our Sun.

For other galaxies, the distances are too great and even our best telescopes cannot resolve individual stars going around their black holes. Instead, astronomers have to carefully study the light from the central region of a galaxy. Through careful spectroscopic measurements of this light, astronomers can apply the Doppler effect to determine the overall motion for all of the stars in that vicinity, and thus obtain an estimate of how massive the black hole must be. This is an effective method, but it takes a lot of telescope time and becomes too difficult for distant galaxies.

Keeping with this tradition of watching things going around other things in order to weigh celestial objects, our pitch angle method also watches spiral arms orbit around their galaxy. However, our task is much easier than other methods because we can measure a black hole's mass from a single image and not require months or years of observing time like other methods. Distance is also less of an issue for us. As long as you can discern spiral structure, you can estimate its black hole mass.

Our method also lends itself to "citizen science". Since internet use has become widespread around the planet, scientists have been able to enlist help from eager volunteers to help analyse the large amounts of data that modern science has generated. For astronomy, the popular citizen science initiative is Galaxy Zoo (https://www.galaxyzoo.org), which allows users to volunteer their time by looking through images of millions of galaxies and classifying features by eye.

Importantly, users are asked to determine the Hubble type of these galaxies by observing the tightness of spiral arms. Suppose you volunteer your time by taking a minute to look at an image of a galaxy (that probably no human has ever looked at before) and you decide that this galaxy best resembles a "Sb" galaxy (see the green spiral from Figure 3). Not only will your classification be recorded in a large database of galaxy morphologies, but you will have also effectively helped humanity estimate that the black hole in this galaxy is around 10 million times the mass of our Sun.

This is a big universe, and there are billions and billions of galaxies out there. Your efforts can help us towards our goal of obtaining a census of black hole masses throughout the universe. Therefore, you can become a census collector helping us determine the demographics of all the black holes residing in all of the spiral galaxies throughout the universe. It beats going door-to-door asking how many people live in each household!

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