OBSERVATIONS OF BLACK HOLES

PROBLEM SET #5 ON WEBWORK – DUE TOMORROW AT MIDNIGHT

HALLOWEEN EXTRA CREDIT!

OBSERVATIONS OF BLACK HOLES

The discovery of AGN and evidence for the presence of black holes therein

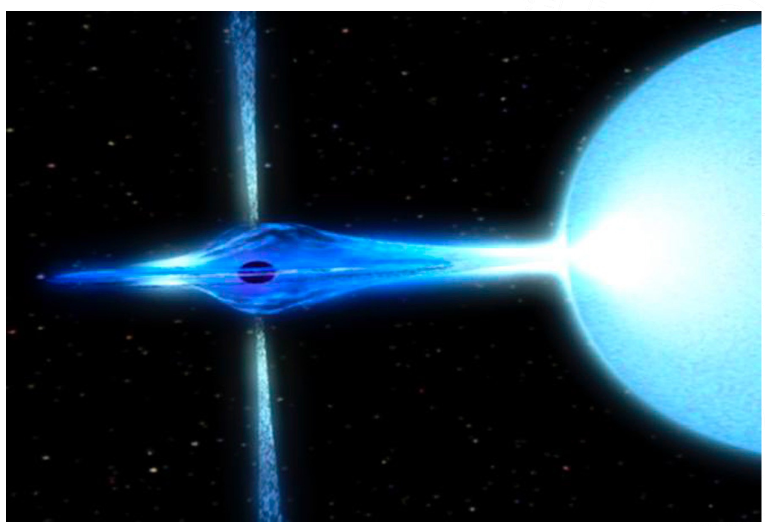
Summary of distinctive features of celestial black holes

The search for stellar-mass black holes

- X-ray and γ-ray emission
- Mass from orbital motion: the Doppler effect

Results for stellar-mass black holes: two almost-certain examples

- Cygnus X-1
- GRO J1655-40



Artist's conception of the star – black hole binary system Cygnus X-1 (Dana Berry, Honeywell/NASA GSFC)

THE (RETROSPECTIVE) DISCOVERY OF BLACK HOLES: SEYFERT GALAXY NUCLEI

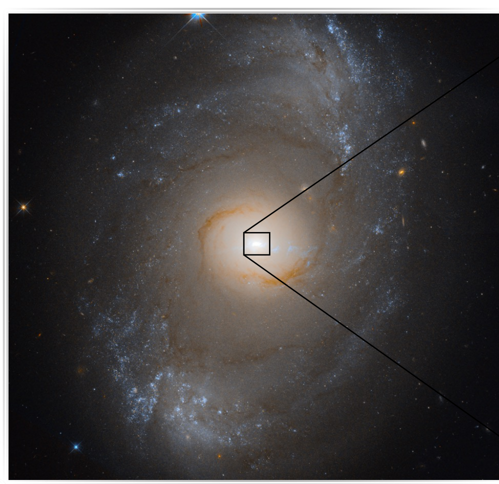
In 1943, Carl Seyfert, following up on a suggestion by Milton Humason, noticed a class of unusual spiral galaxies, now called Seyfert galaxies.

- Unlike other galaxies, in short-exposure photographs they look like stars; long exposures reveal that each bright starlike object actually lies at the nucleus of a galaxy.
- The starlike nucleus has lots of ionized gas, with a peculiar, broad range of ionization states and Doppler shifts indicative of very high speeds (thousands of km/s).
- The starlike nucleus is also much bluer than clusters of normal stars.

Seyfert noted that there did not seem to be a plausible way to explain the starlike nucleus as a collection of stars.

Seyfert

SEYFERT GALAXY NGC 4151

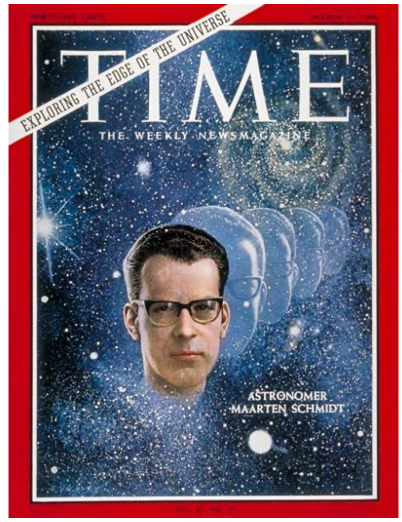


Long exposure showing the central "bulge" and spiral arms (HST)

X-ray (blue, Chandra), visible (yellow), and radio (red, VLA) image of the center of the galaxy.

THE DISCOVERY OF BLACK HOLES: QUASARS

- Discovered by radio astronomers: small, "starlike," bright sources of radio emission (1950s)
- First identified as stars with extremely peculiar spectra by visible-light astronomers (1950s)
- Maarten Schmidt (1963) was the first to realize that the spectrum of one quasar, 3C 273, was very much like a common galaxy spectrum but seen with a Doppler shift of about 48,000 km/s – 16% of the speed of light.



Maarten Schmidt in 1963 (Time Magazine)

THE DISCOVERY OF BLACK HOLES: QUASARS

- High speed with respect to us: the **quasars are very distant.** 3C 273 is measured to be about 2 billion light years away, much further than any galaxy known in the early 1960s.
- Yet they are bright: the **quasars are extremely powerful.** 3C 273 has an average luminosity of $10^{12} L_{\odot}$, about 100 times the power output of the entire Milky Way galaxy.

Observations also show that the power parts of **quasars are very small.**

- Radio-astronomical observations show directly that most of the brightness in 3C 273 is concentrated in a space smaller than 10 light years in diameter, a factor of about 20,000 smaller than the Milky Way galaxy.
- The brightness of quasars is high, and randomly, variable.
  - 3C 273 can change in brightness by a factor of 3 in only a **month**.
  - This means that its power is concentrated in a region with a diameter no larger than **one light-month**, 7.9×10^{11} km. For comparison, Pluto's orbital diameter is about 10^{10} km.
- ***Major*** problem: How can so much power be produced in such a small space?

WHY DOES RAPIDLY-VARIABLE BRIGHTNESS MEAN SMALL SIZE?

If a quasar's brightness varies a lot in one month, why does that mean that the power comes from a region no bigger than a light-month?

A. If it were any bigger, the energy input that "throws the switch" would have to travel faster than the speed of light.
B. Relativistic length contraction: it just looks smaller to a distant observer.
C. Gravitational time dilation: the slow arrival over a month of the brighter signal must mean that the region near the horizon of a black hole is involved.

HOW ARE QUASARS POWERED?

Requirements: Need to make $10^{12} L_{\odot}$ in a sphere with circumference $2.5{\times}10^{12}$ km (0.26 ly) or smaller.

Here are a few ways to produce that large of a luminosity in that small of a space.

- **10^7 stars of maximum brightness, $10^5 L_{\odot}$**

  Problem: Such stars only live 10^6 years or so. We see so many quasars in the sky that they must represent a phenomenon longer lived than that.

HOW ARE QUASARS POWERED?

- $\mathbf{10^{12}}$ **solar-type stars: each with** $\boldsymbol{L = 1L_\odot, M = 1M_\odot}$

  Problem: Stars would typically be only about $6{\times}10^{12}$ cm apart, less than half the distance between the Earth and the Sun. They would collide frequently.

  They would also weigh $10^{12}M_\odot$. The Schwarzschild circumference for that mass is

$$C_S = \frac{4\pi GM}{c^2} = \frac{4\pi(6.67{\times}10^{-8}\ \mathrm{cm^3/g\ s^2})(10^{12})(2{\times}10^{33}\mathrm{g})}{(3{\times}10^{10}\ \mathrm{cm/s})^2}$$

$$C_S = 1.9{\times}10^{18}\mathrm{cm} = 2.0\ \mathrm{ly}$$

  Larger than that of the space in which they are confined. Thus, if you assembled this collection of stars in that small of a space, you would have made a **black hole**, not a cluster of stars.

HOW ARE QUASARS POWERED?

- **Accretion of mass onto a black hole**
  - Luminosity = energy/time ($10^{12}L_\odot = 3.8{\times}10^{45}$ erg/s)

    Energy = luminosity x time

    But energy (radiated) = total energy × efficiency = mc^2 × efficiency, so

    Mass = luminosity × time / (efficiency × c^2)
  - For a time of 1 year ($3.16{\times}10^7$ s) and an efficiency of 10%, we get

$$\mathrm{mass} = \frac{(3.8{\times}10^{45}\ \mathrm{erg/s})(3.16{\times}10^{7}\mathrm{s})}{(0.1)(3{\times}10^{10}\ \mathrm{cm/s})^2} = 1.3{\times}10^{33}\mathrm{g} = 0.7M_\odot$$

  The black hole would have to swallow $0.7M_\odot$ per year, a very small amount on a galactic scale. **No problem.**

DISTINCTIVE FEATURES THAT INDICATE THE PRESENCE OF A BLACK HOLE

Observe **two or more** of these features to “find” a black hole:

- **Gravitational deflection of light (gravitational lensing)** by an amount requiring black hole masses and sizes
- **X-ray and/or γ-ray emission** from ionized gas falling into the black hole
- **Orbital motion of nearby stars or gas clouds** that can be used to infer the mass of (perhaps invisible) companions: a mass too large to be a white dwarf or neutron star might correspond to a black hole.
- **Motion close to the speed of light** or apparently greater than the speed of light (“superluminal motion”)
- **Extremely large luminosity** that cannot be easily explained by normal stellar energy generation
- Direct observation of a large, massive **accretion disk**

STELLAR-MASS BLACK HOLES

By this, we mean black holes which formed by the gravitational collapse of dead stars that were too massive to become neutron stars or white dwarfs.

Best clues:

- High-energy light (X/γ-rays): gives promising, but not completely unambiguous, detections of black holes.
- Orbital motion of companion stars
  - Orbit size and speed in addition to Newton’s laws can be used to work out the **mass** of a visibly-dim (but perhaps X-ray bright) companion. If it is more than $2.2M_{\odot}$, then it cannot be a neutron star (or a white dwarf).
  - We cannot usually resolve the details of the orbit directly in images, but we can measure orbital speeds and periods well enough to work out what the orbit is, using the Doppler effect.

HIGH-ENERGY LIGHT FROM STELLAR-MASS BLACK HOLES

X-ray or γ-ray emission:

High-energy light should be emitted by material falling into black holes; this should be one of the principle signatures of a black hole, because it is difficult for ordinary astronomical objects to emit X-rays.

- **Search for such objects near visible stars.** Most stars have stellar companions; if such a companion became a black hole, and the two were close enough together, material from the visible star could fall into the black hole, creating an X-ray source.
- **Difficulty**: X-rays are absorbed strongly by the Earth's atmosphere (and by interstellar gas and dust). Observations must take place from outside the atmosphere (i.e. from satellites).

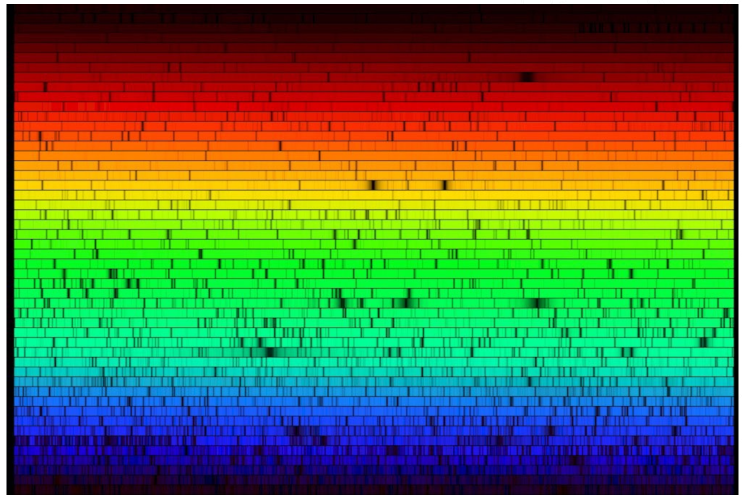
HIGH-ENERGY LIGHT FROM BLACK HOLES

- X-ray detectors on rockets discovered the first stellar sources of high-energy light (Sco X-1, 1962).
- Many more were found by X-ray detectors on satellites (*Uhuru, Ginga*) and by X-ray and γ-ray telescopes and detectors on satellites (*Einstein, ROSAT, Compton GRO*).
- Some of the objects fit the description of accretion by black holes from companion stars.
- **Most do not**: some other types of stars also turned out unexpectedly to be bright sources of X-rays. Thus, X-ray emission is helpful, but not sufficient, in identifying a black hole.
- Fortunately, some of the X-ray objects have visible stellar companions from whose orbits we can estimate the mass of the corresponding X-ray objects.

ORBITAL MOTION & THE DETECTION OF BLACK HOLES

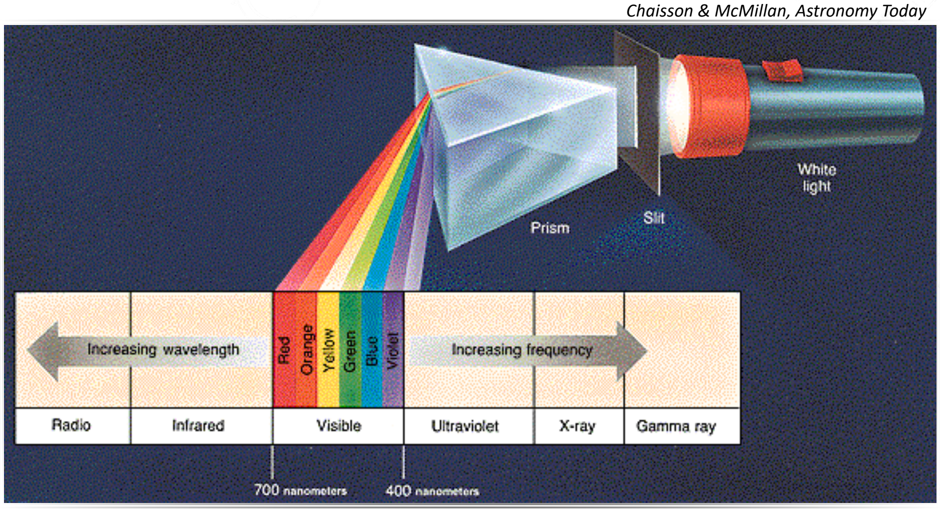
The stars have narrow dark lines in their spectra: specific wavelengths at which the stars are dark.

In moving stars, these lines are shifted to different wavelengths due to the Doppler effect.



The spectrum of the Sun. For ease of viewing, the spectrum has been sliced into segments stacked vertically: wavelength decreases to the right along each segment, and down along the image (N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF).

Chaisson & McMillan, Astronomy Today



ORBITAL MOTION & THE DETECTION OF BLACK HOLES

The spectrum is measured by dispersing the light with a prism or diffraction grating (using a star instead of a flashlight, of course).

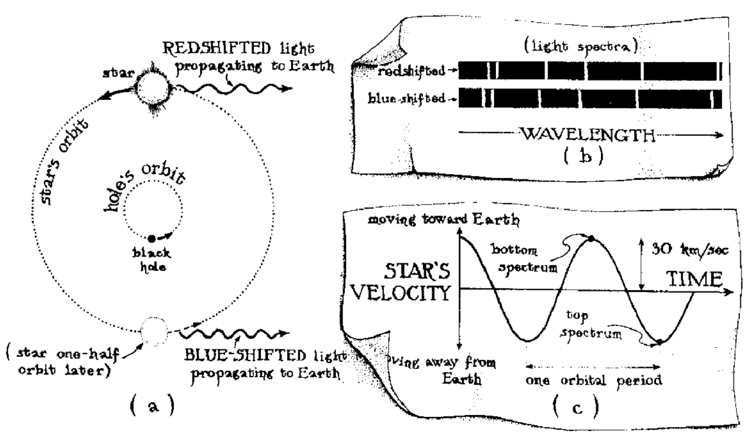
MEASURING VELOCITIES FROM THE DOPPLER EFFECT

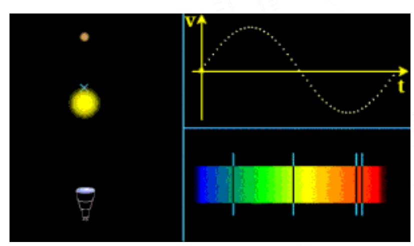
The Doppler effect: shift in wavelength of light between when it is emitted and when it is detected, owing to the motion of the source of light:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{V}{c} \quad \text{or} \quad \lambda = \lambda_0\left(1 + \frac{V}{c}\right) \quad \text{or} \quad V = c\left(\frac{\lambda}{\lambda_0} - 1\right)$$

where

- λ is the wavelength that the observer sees
- λ_0 is the wavelength in the rest frame of the object that emitted the light
- V is the velocity of the object with respect to the observer
- c is the speed of light





ORBITAL MOTION & THE DETECTION OF BLACK HOLES

You can deduce the orbital speed from the maximum and minimum Doppler shifts.

DOPPLER EFFECT EXAMPLE

Example: Suppose that a star has an absorption line at a wavelength $\lambda_0 = 5000.0\ \text{Å}$ (seen in its rest frame) and moves toward us at 100 km/s. At what wavelength do we see the absorption line?

$$\lambda = \lambda_0 \left(1 + \frac{V}{c}\right) = (5000.0\ \text{Å})\left(1 + \frac{-100\ \text{km/s}}{3\times10^5\ \text{km/s}}\right)$$

$$\lambda = 4998.3\ \text{Å}$$

Note: $1\ \text{Å} = 10^{-10}\text{m}$

DOPPLER EFFECT EXAMPLE

A star revolves around a very massive, dark object at rest with respect to us; the speed of revolution is 29.979 km/s, and the revolution period is several months. What is the **maximum** observed value of wavelength for an absorption line with rest wavelength $\lambda_0 = 5000.0\ \text{Å}$, over the course of a few years?

DOPPLER EFFECT EXAMPLE

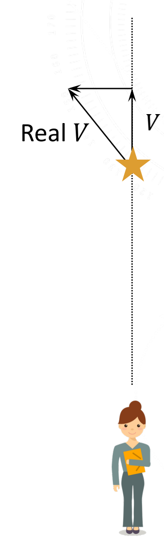
Same star: it revolves around a very massive, dark object at rest with respect to us; the speed of revolution is 29.979 km/s, and the revolution period is several months. What is the **minimum** observed value of wavelength for an absorption line with rest wavelength $\lambda_0 = 5000.0\ \text{Å}$, over the course of a few years?

SLIGHT COMPLICATIONS WITH THE "DOPPLER VELOCITY"

The velocity V in the Doppler shift formula is actually the component of the moving object's velocity along the observer's line of sight.

- V only equals the object's real velocity if the object is moving directly along the line of sight (V here is called the **radial velocity**).
- An object moving perpendicular to the line of sight has no Doppler shift.

The value of the velocity V that goes into, or comes out of, the formulas is positive if the object moves away from the observer and is negative if the object moves toward the observer.



SLIGHT COMPLICATIONS WITH THE "DOPPLER VELOCITY"

Any **overall** velocity v of the system must be added to the rotational velocity V to get the Doppler velocity. This would make the Doppler velocity from rotation vary between $v + V$ and $v - V$ during an orbital period.