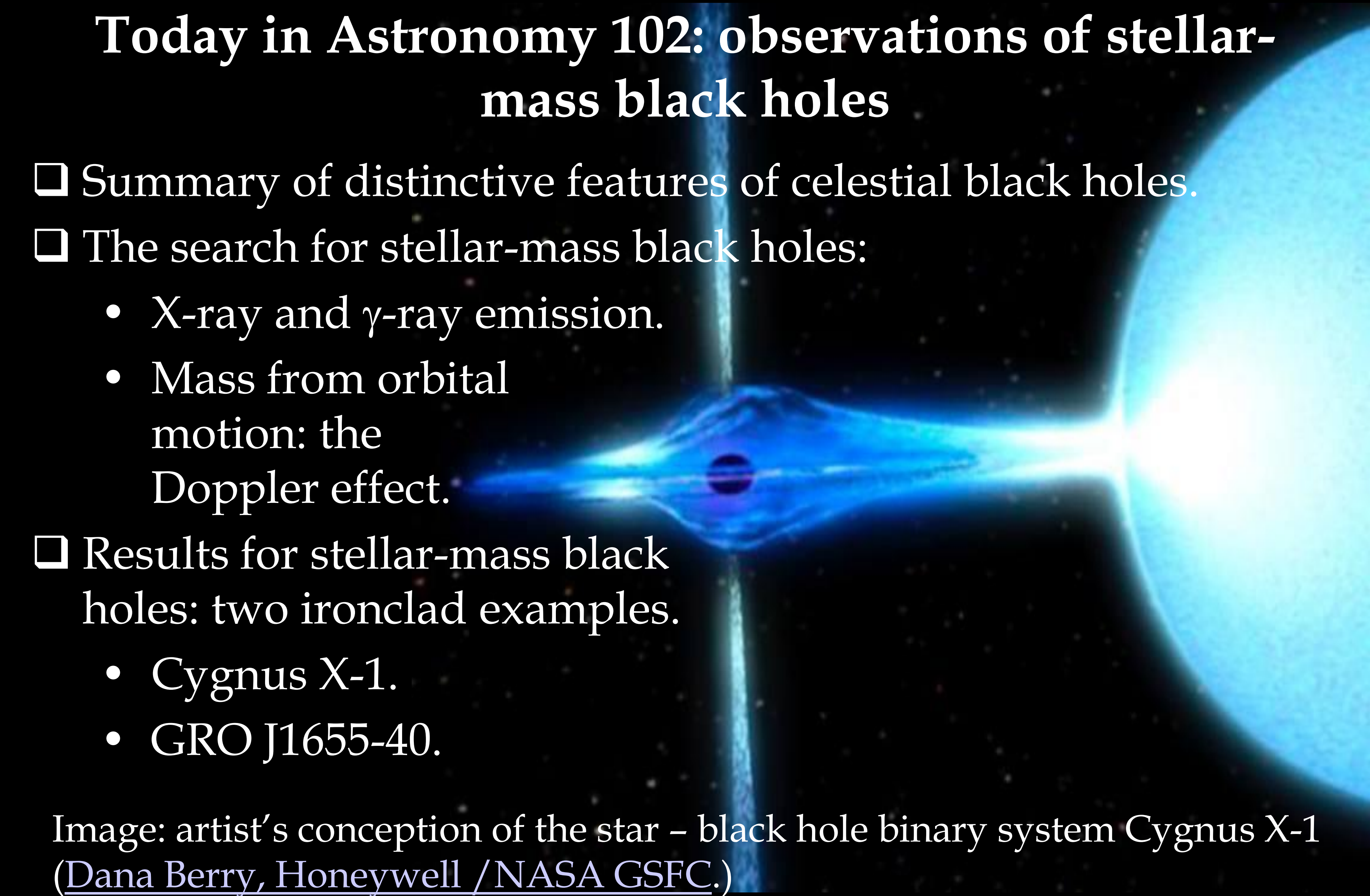
Today in Astronomy 102: observations of stellar-mass black holes



- 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 ironclad examples.
  - Cygnus X-1.
  - GRO J1655-40.

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

Distinctive features that can indicate the presence of a black hole

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

- ☐ **Gravitational deflection of light**, 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 a 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 explained easily by normal stellar energy generation.
- ☐ Direct observation of a large, massive **accretion disk**.

Stellar-mass black holes

By this we mean black holes formed by the gravitational collapse of dead stars that are 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, speed plus Newton's laws can be used to work out the **mass** of a visibly-dim (but perhaps X-ray bright) companion. If it's more than 2 $M_\odot$ …
  - We can't 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, in fact, should be one of the principal signatures of a black hole because it is hard 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).

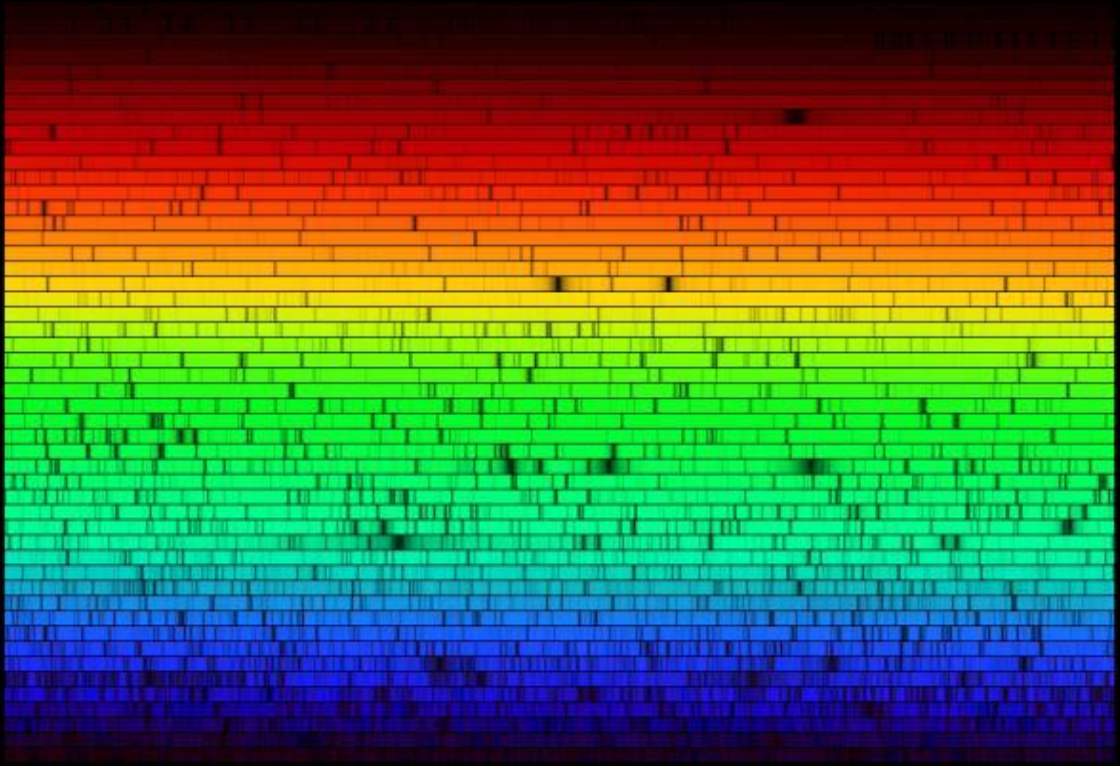
High-energy light from black holes (continued)

- ☐ 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 sorts 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 and the detection of black holes

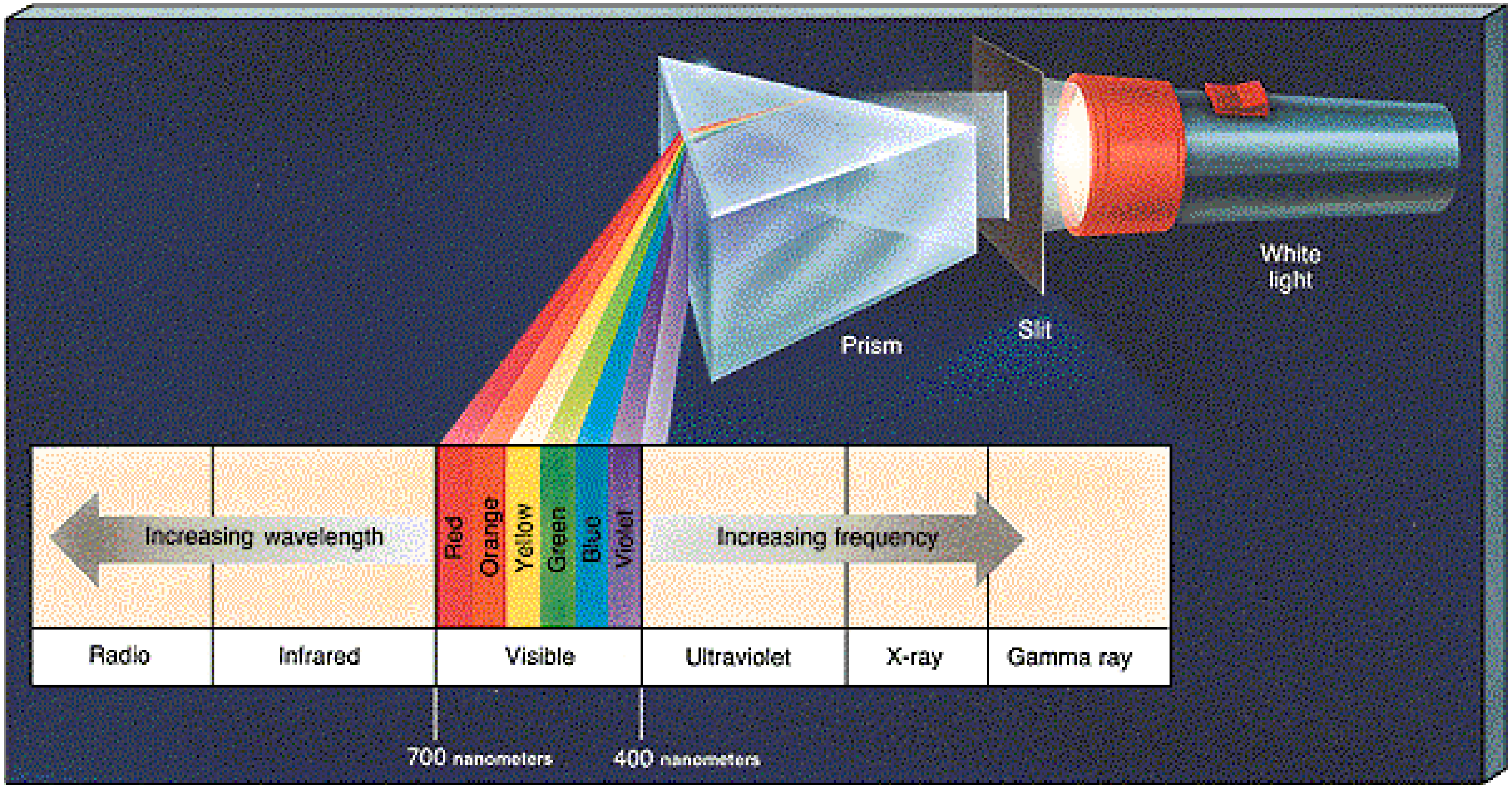
The stars have narrow dark lines in their spectra: specific wavelengths at which the stars are dark. (Sun’s visible spectrum at right.)

In moving stars these lines are shifted to different wavelengths due to the Doppler effect (see lecture notes for 22 September 2011).



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 page. (N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF.)

Orbital motion and the detection of black holes (continued)



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

Figure: Chaisson and McMillan, *Astronomy today*

Measuring velocities from the Doppler effect

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

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{V}{c}$$

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

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

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 and the detection of black holes

Can deduce orbital speed from maximum and minimum Doppler shifts:

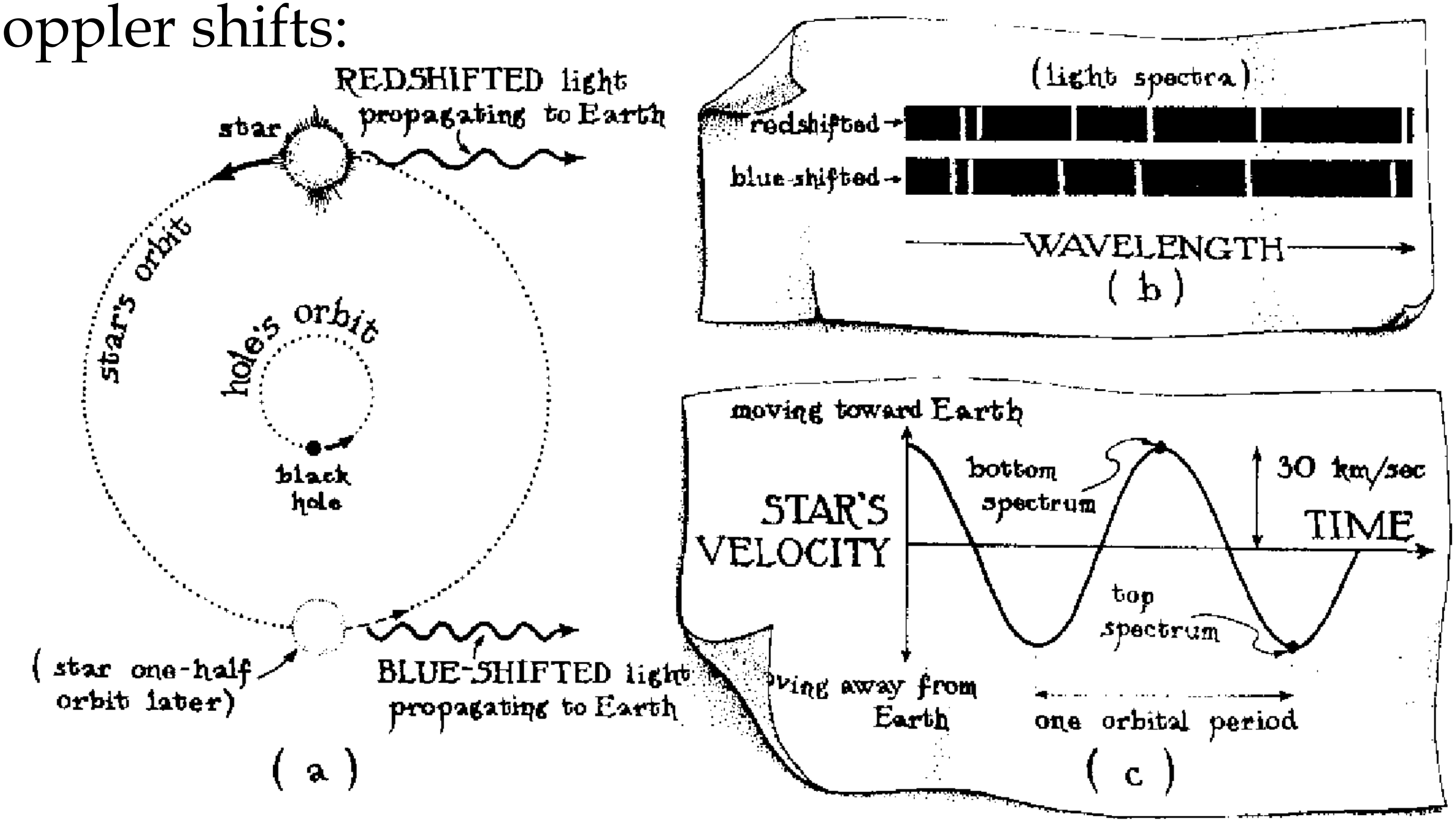


Figure: Thorne, *Black holes and time warps*

Doppler effect: example and simulation

Example. Suppose a star has an absorption line at a wavelength $\lambda_0 = 5\text{x}10^{-5}$ cm (seen in its rest frame) and moves toward us at 100 km/sec. At what wavelength do we see the absorption line?

$$\lambda = \lambda_0\left(1+\frac{V}{c}\right) = \left(5.0000\times10^{-5}\ \text{cm}\right)\left(1+\frac{-100\ \frac{\text{km}}{\text{sec}}}{3.00\times10^{5}\ \frac{\text{km}}{\text{sec}}}\right)$$

$$= 4.9983\times10^{-5}\ \text{cm}.$$

More examples will be worked out in Recitation.

Simulation. This program, which is accessible from the on-line lecture notes, was written in Java by Prof. Terry Herter at Cornell, for his AST 101 class.

Now, you try

A star revolves around a very massive, dark object at rest with respect to us; the speed of revolution is 29.979 km/sec, and the revolution period several months. What is the **maximum** observed value of wavelength, for an absorption line with rest wavelength $\lambda_0 = 5\text{x}10^{-5}$ cm, over the course of a few years?

$$\lambda = \lambda_0 \left(1 + \frac{V}{c} \right) = ?$$

A. 4.9995×10^{-5} cm B. 5.0000×10^{-5} cm C. 5.0005×10^{-5} cm

D. 5.0010×10^{-5} cm E. 5.0015×10^{-5} cm

Now, you try

Same star: it revolves around a very massive, dark object at rest with respect to us; the speed of revolution is 29.979 km/sec, and the revolution period several months. What is the **minimum** observed value of wavelength, for an absorption line with rest wavelength $\lambda_0 = 5\text{x}10^{-5}$ cm, over the course of a few years?

$$\lambda = \lambda_0 \left(1 + \frac{V}{c} \right) = ?$$

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B. 5.0000×10^{-5} cm
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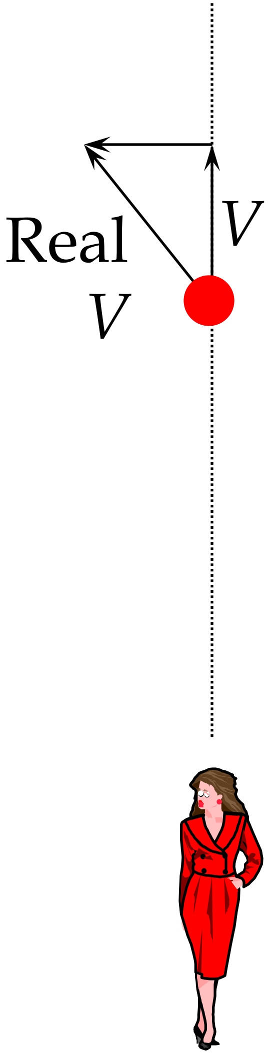
D. 5.0010×10^{-5} cm
E. 5.0015×10^{-5} cm

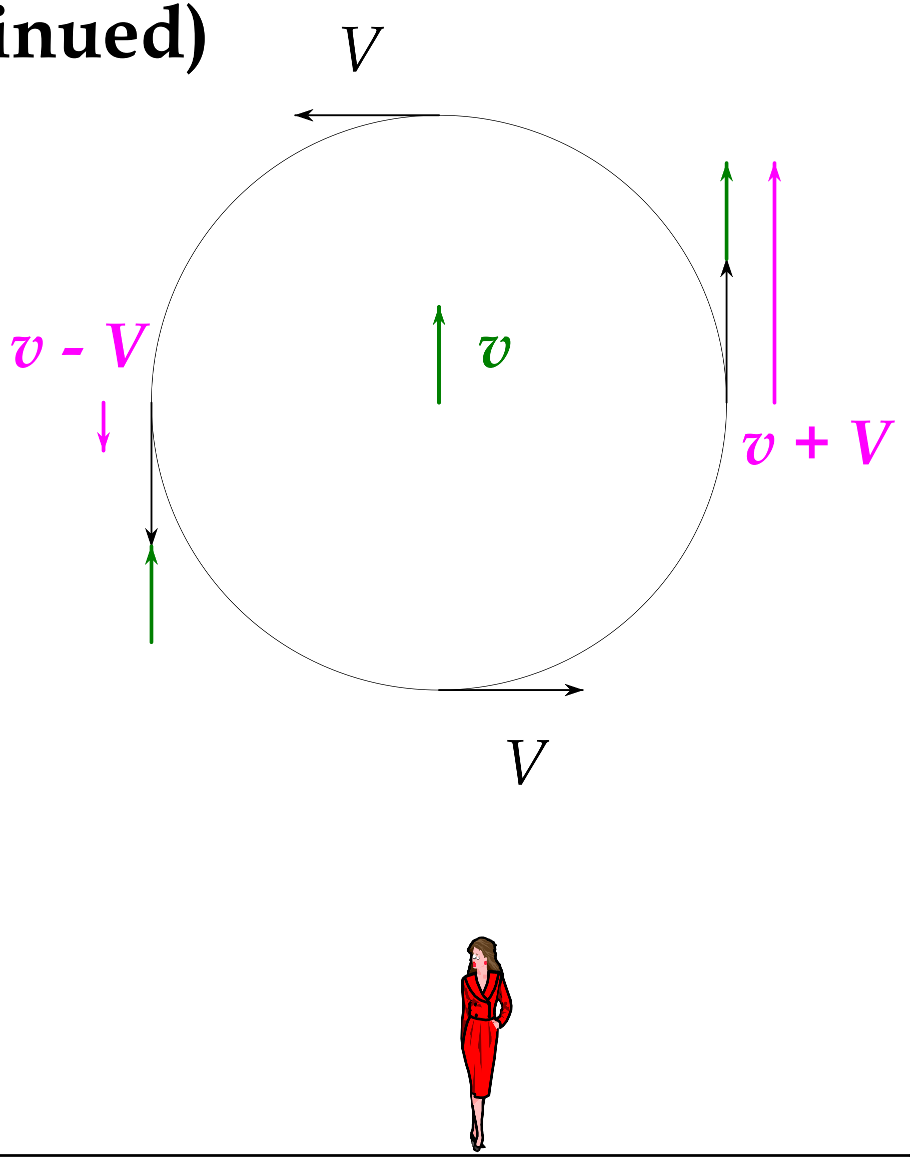
Slight complications with the "Doppler velocity"

- 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 right 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 a positive number if the object moves away from the observer, and is a negative number if the object moves toward the observer.



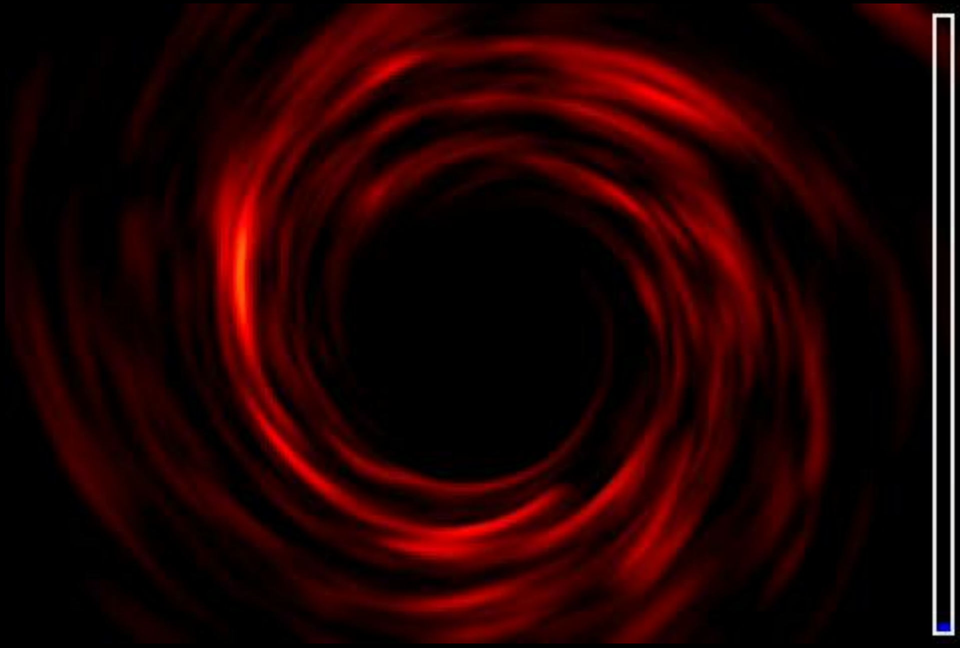
Slight complications with the “Doppler velocity” (continued)

- 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.



Mid-lecture Break.

Homework #4 is due at 5:30 PM on Friday, 4 November.



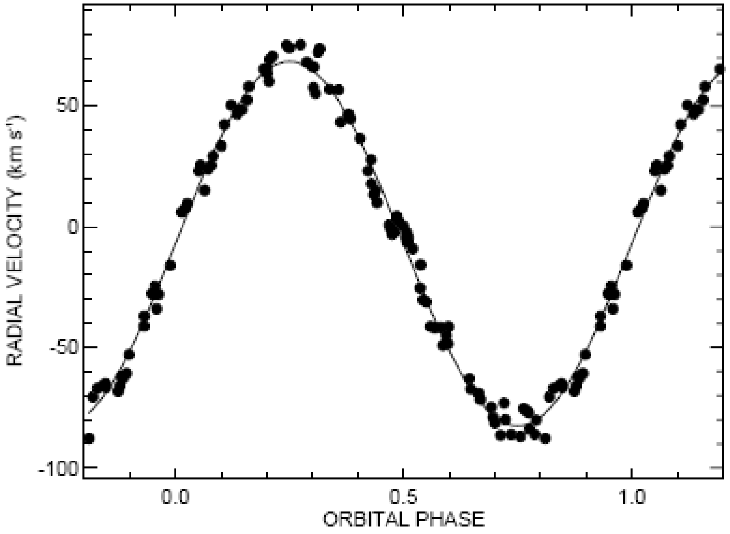
Simulation of a black hole accretion disk, with the view changing from pole-on to almost edge on. By Phil Armitage and Chris Reynolds.

Discovery of "stellar" black holes: Cygnus X-1

Cygnus X-1 (a.k.a. Cygnus XR-1) is a bright X-ray source, the second brightest in the sky.

- ☐ Its X-ray brightness varies dramatically on time scales of 0.001 sec: the X-ray object must be about 0.003 light-seconds (940 km) in circumference.
- ☐ Essentially at the same position as the X-ray source is a bright star that appears to be in orbital motion. No other visible star nearby exhibits orbital motion; the bright star's companion is invisible. Other stars like it are not bright in X rays. It is thus reasonable to assume that the bright star's invisible companion is the X-ray source.
- ☐ The star and the invisible companion are too close together for telescopes to **resolve** them from our distance.

Cygnus X-1 (continued)



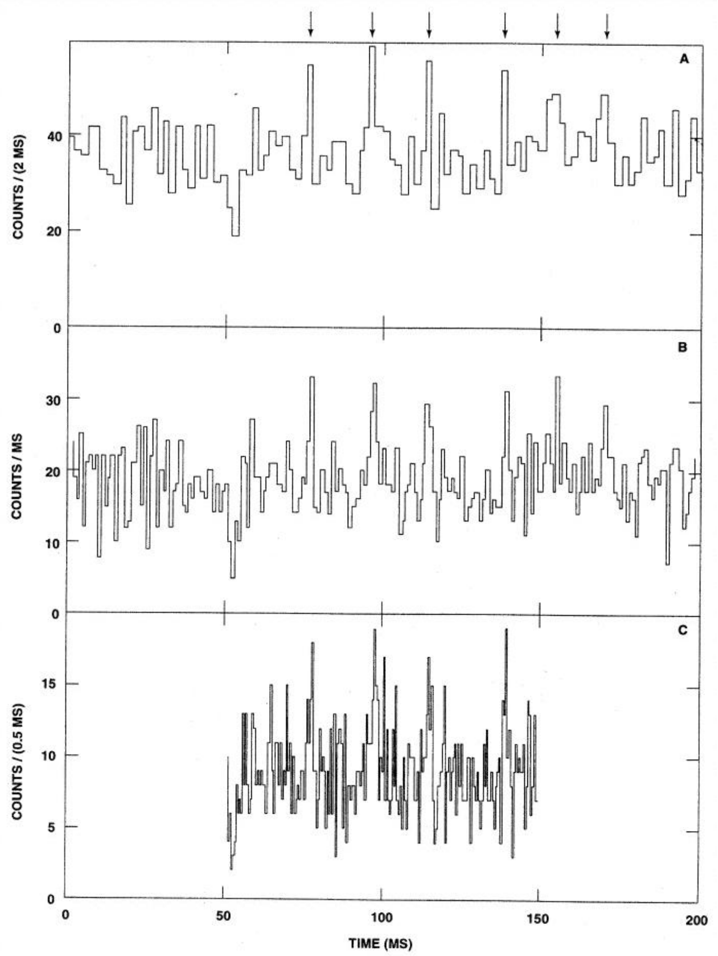
Measured orbital motion of HDE 226868 ([Gies et al. 2003](#))

- Orbital parameters of the bright star (HDE 226868): distance 6000 light years, revolution period of 5.6 days, orbital circumference 1.8×10^8 km, mass of HDE 226868 about 24 $M_\odot$.
- The tilt of the orbit has been determined, with difficulty and not terribly accurately: the rotation axis makes an angle of about 48° with respect to our line of sight ([Iorio 2008](#)).
- Applying these inputs to Newton's laws of motion, a mass between 7 and 11 $M_\odot$ is derived for the invisible companion; most probable value 9 $M_\odot$. A black hole?

“Death spirals” in Cygnus X-1: seeing the event horizon itself?

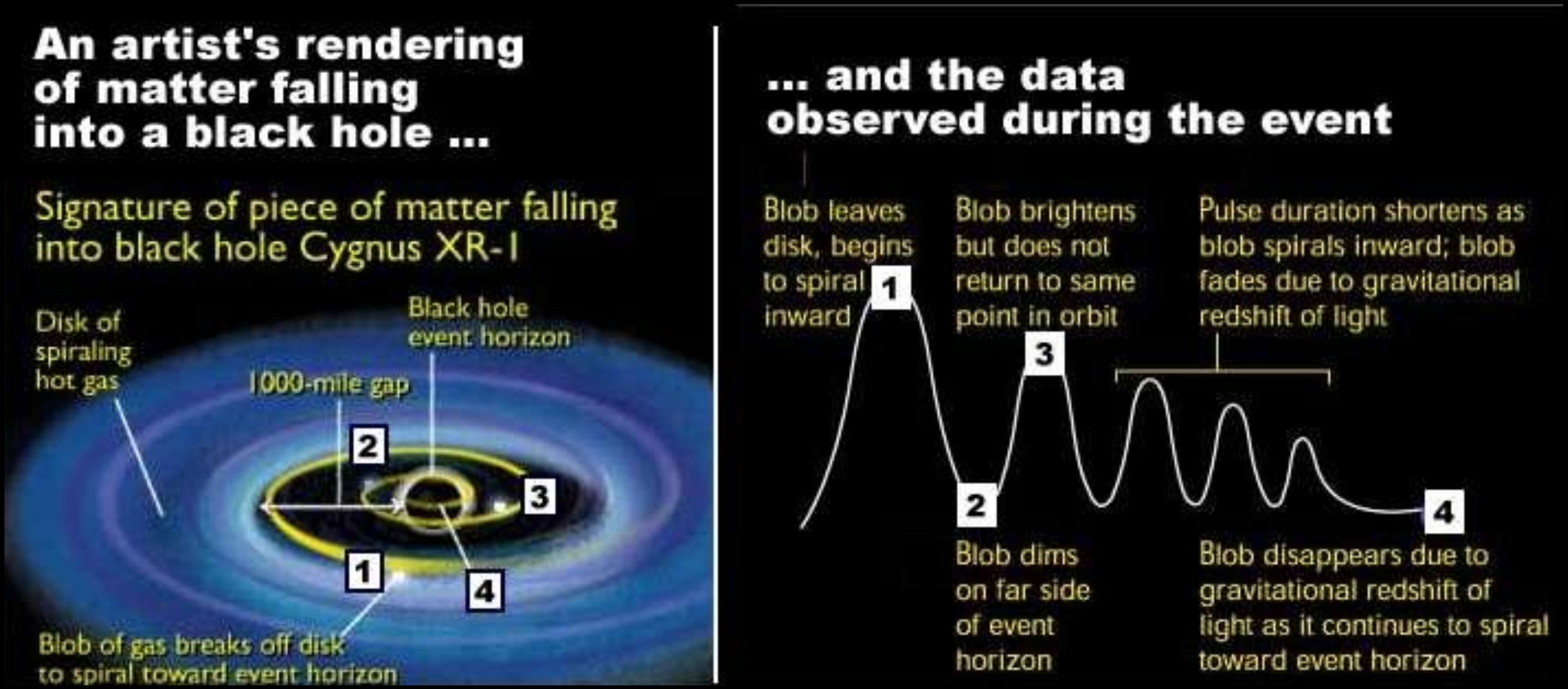
Occasionally Cyg X-1 emits short bursts of light seen at ultraviolet wavelengths, in the form of a train of pulses that dies off toward the end. One such burst, seen with the Hubble Space Telescope by [Joe Dolan (2001)](), is shown at right.

- Pulse period close to orbital period near innermost stable orbit.
- Are we seeing material falling from an unstable orbit, and passing behind the horizon once per orbit?



“Death spirals” in Cygnus X-1: seeing the event horizon itself? (continued)

Here’s how that would work. (Illustration by Ann Field, NASA/STScI.)



Cygnus X-1: summary

- ☐ Too small, too X-ray bright, and too faint at visible wavelengths to be a 9 $M_\odot$ star.
- ☐ Far too massive to be a white dwarf or neutron star.
- ☐ Evidence of orbit instability, **and of an event horizon**, on precisely the scales expected for a 9 $M_\odot$ black hole.

The simplest, and in fact least exotic, interpretation of the observations is that Cygnus X-1 consists of a 24 $M_\odot$ star and a 9 $M_\odot$ black hole in orbit around each other.

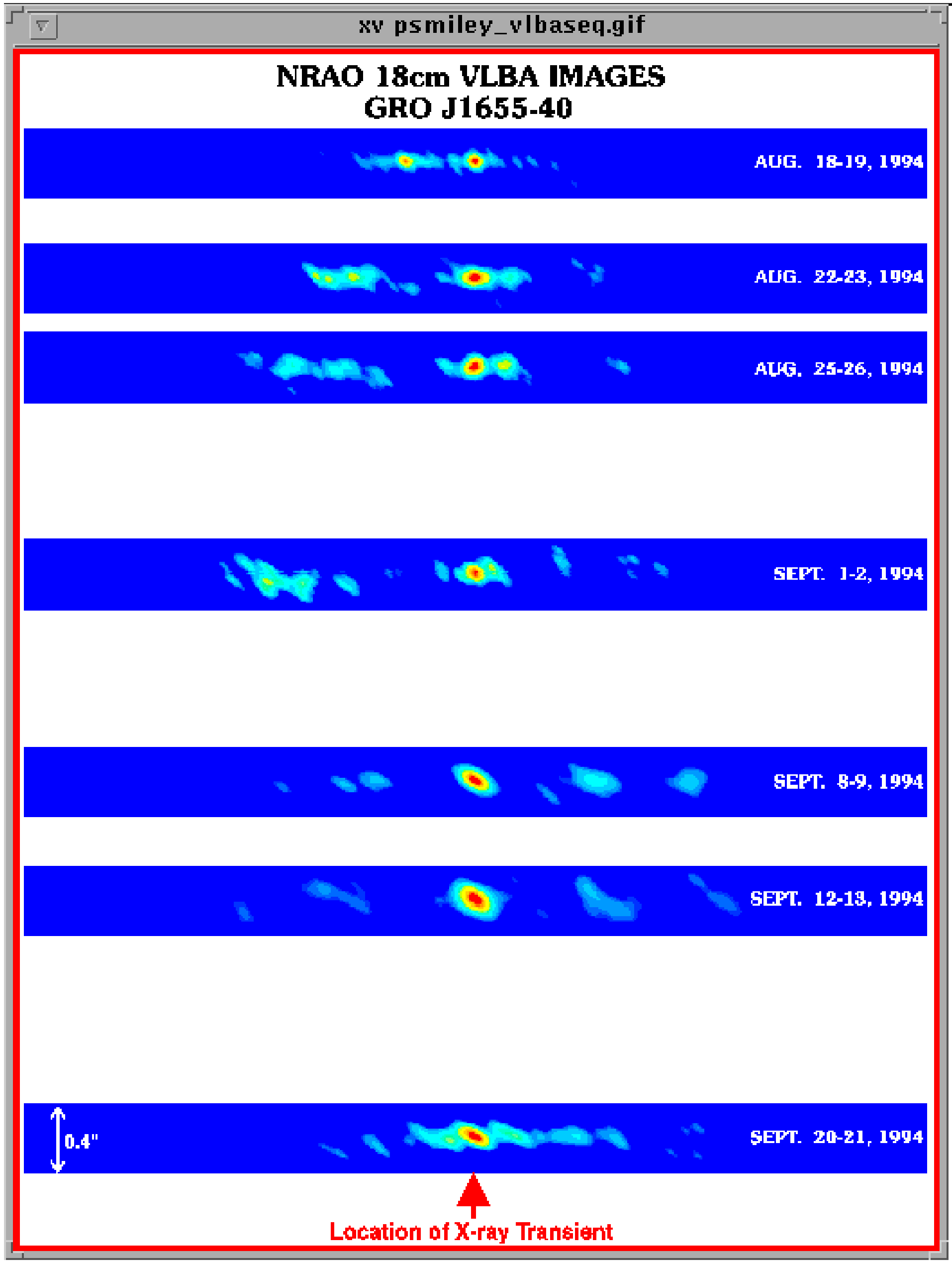
(Stephen Hawking, who used to assert that Cyg X-1 does not contain a black hole, has conceded his celebrated bet with Kip Thorne on this subject; see Thorne's book, p. 315.)

Discovery of "stellar" black holes: GRO J1655-40

GRO J1655-40 (a.k.a. Nova Scorpii 1994) is an X-ray transient source discovered by NASA's *Compton* Gamma-Ray Observatory (GRO) in 1994.

- ❑ Rapidly-variable emission in its X-ray bursts: the X-ray object is a few hundred km around.
- ❑ The X-ray source has a stellar companion, a star rather similar to the Sun (about 1.1 $M_\odot$); the X-ray source and the visible star revolve around each other with a period of 2.92 days. Their distance from us is measured to be 6500 light years.
- ❑ A stroke of luck: it is an **eclipsing** system, so the orbit is known to be tilted edge on to our line of sight.
- ❑ Thus we know the mass of the X-ray bright companion rather accurately: it must be between 5.5 and 7.9 $M_\odot$, with a most probable value of 7.0 $M_\odot$. (Shahbaz *et al.* 1999)
- ❑ Also has radio jets with motions close to the speed of light!

GRO J1655-40 (continued)



Two jets, perpendicular to the plane of the orbit, with ejection speed 0.92*c*.

Radio images: R. Hjellming and M. Rupen, NRAO.

GRO J1655-40 spins, too.

We expect it to spin, but now we can demonstrate this:

A 7 $M_\odot$ black hole has a horizon circumference 130 km, and if it doesn't spin its innermost stable orbit circumference is 390 km. Material in this orbit will circle the black hole **314 times per second.**

- ☐ However, one often sees the X-ray brightness of GRO J1655-40 modulate at **450 times per second** for long stretches of time (Strohmayer 2001).
- ☐ Nothing besides very hot material in a stable orbit can do this so reproducibly at this frequency.
- ☐ Thus there are stable orbits closer to the black hole than they could be if it didn't spin.

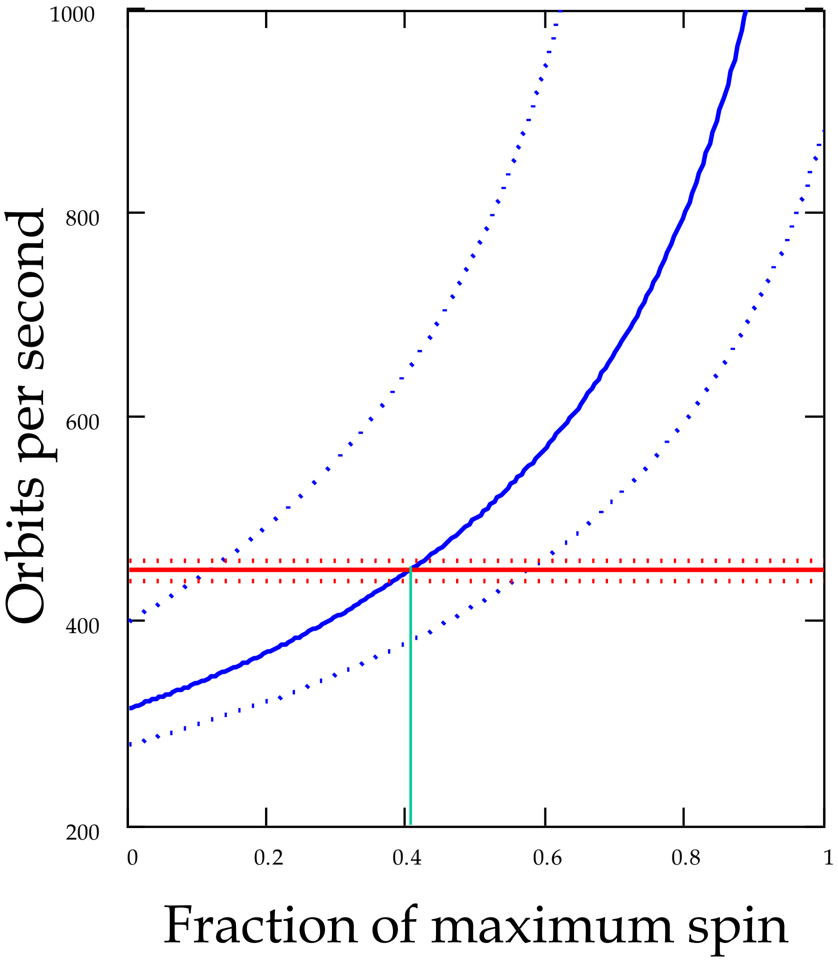
GRO J1655-40 spins, too (continued).

Most probably, the black hole in GRO J1655-40 is spinning at about 40% of its maximum rate. Within the uncertainties the spin rate lies in the range 12%-58% of maximum; zero spin is quite improbable.

In blue: innermost stable orbits per second for 7.0 $M_\odot$ black holes, with uncertainties.

In red: measured orbits per second, with uncertainties

(by Tod Strohmayer, with the *Rossi* X-ray Timing Explorer).



GRO J1655-40 (continued)

The invisible companion object:

- ☐ X-ray bright.
- ☐ Too small to be a white dwarf.
- ☐ Too massive to be either a white dwarf or a neutron star.
- ☐ Associated with ejection at 92% of the speed of light.
- ☐ Associated with orbital frequencies appropriate for a spinning black hole.

These properties make GRO J1655-40 more likely to harbor a black hole than any other object we know.

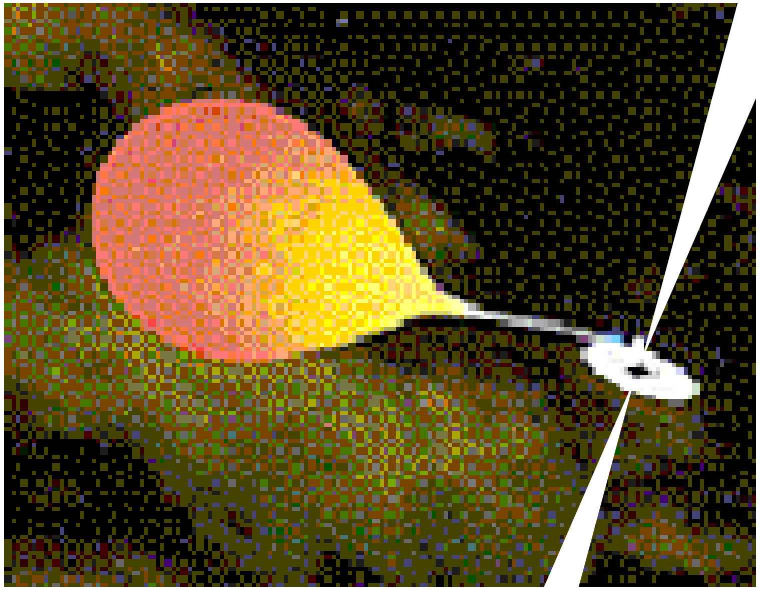


Image: artist's conception of GRO J1655-40, after Chaisson and McMillan, *Astronomy Today*.