Physics Qualifying Exam

Tuesday, May 19, 2020 12:03 PM

(7) Describe three methods for detecting extrasolar planets and indicate the contribution of each to the population of known exoplanets.

i. Radial Velocity

The presence of an exoplanet will cause a star to orbit around the system's center of mass.
A spectrum of the star can be taken multiple times and compared.
If the star is indeed "wobbling" about a center of mass this will cause a doppler shift which will look like the spectrum being shifted in wavelength by some amount.
This shift produces a radial velocity measurement, which if the mass of the star is known, a minimum mass for the planet can be estimated.
This method is best at detecting hot Jupiters which are very massive planets that are close to the host star.

ii. Transit Method

The presence of an exoplanet that is passing directly in front of a star will cause the star's light to dim, temporarily.
A light curve of the star can be produced by measuring the amount of light from the star multiple times and looking for periodic dips or transit depths. The transit depth gives you the radius of the exoplanet, if the radius of the star is known.
The Kepler space telescope has found thousands of new planets with a range of masses this way. The caveat is that the planet likely needs to be close to the host star in order for it to be caught.

iii. Direct Imaging

The presence of an exoplanet can sometimes be directly imaged.
A coronagraph is used to block light from the star, so the reflected light on the planets can be visible.
The light from the planet can be used to infer its radius/mass.
This method is best at detecting planets in star systems close to earth, and when the planet is very large and far enough from the star that its light can be separated. Only a few planets have been detected this way.

Follow-up 1: For a planet discovered by radial velocity, transits add very useful information.
What can we learn from transits that isn't clear from the change in radial velocity?

Radial velocities can give a minimum mass, but not a specific mass estimate. Degeneracies occur because the inclination angle is not known.
The transit method requires the planet to be edge-on so the inclination angle can be inferred from that.
The transit method also gives a radius, which is measured through the transit depth.

Follow-up 2: What kinds of selection bias(es) might occur due to each observation method?

Radial Velocity: The only observed planets with this method are large, close to the star, and have an inclination angle such that the system is "edge-on" rather than "face-on". The radial velocity shift must be resolvable from noise: the velocity with which the star is orbiting the center of mass must be great enough that we can detect it. These velocities are fairly low in terms of radial velocities, roughly 10^{-2} **to** 10^{1} meters per second, the very best that's been done, I believe, is around 1 meter per second, so the number and type of planets you can observe is fairly constrained.

Transit Method: This also has a dependence on inclination angle. The planet must pass in front of the star, from earth's perspective, so that the light can be changed at all. While this method can detect a wider range of masses than either the radial velocity or direct imaging, it still can't detect all masses. The planet has to be large enough that it can affect the stellar light at all.

Direct Imaging: This method requires that the host star is close enough that the system is resolvable. The planet has to also be far enough from the star, that a coronagraph wouldn't also cover it. It requires that the planet be able to efficiently emit reflected or absorbed light from the host star. This limits the range of masses, and possibly planetary albedos, that could be detected.

(13) Describe linear and circular polarizations of electromagnetic waves and give examples of their relevance to astronomical observations.

Light is a transverse wave that can have either linear or circular polarizations.

In general light is not polarized, when the electric field is hitting your detector, it could do so from any direction.

Polarization means the light is confined to certain directions.

Linear polarization refers to the oscillation of light in a single plane, if you were to look directly into the path of a light ray, you would only see an oscillation up or down. Phase angles are either $0°$ or $180°$.

Circular polarization is in two planes with $90°$ phase difference. Phase angles are either $90°$ or $270°$, the amplitudes of the plan waves are equal.

Circular polarization can oscillate clockwise or counter clockwise, referring to a right or left handedness.

Polarization Examples

Synchrotron radiation can be linear or circularized, it depends on the viewing angle. It is linear if you're looking directly at it edge-on but if you're looking like from above, face-on, then it would appear circular.

Dust can be polarized by magnetic field lines (there are super neat galactic maps of this) I believe this is linear as magnetic fields are also linear.

The CMB polarizations are linear.

Follow-up 1: Linear polarization of the light from a supernova is used as evidence that the explosion is not spherical. This happens because linearly polarized regions of the image no longer cancel. What process leads to the polarization of regions in the explosion's resolved image? (Hint: this operates also in the CMB.)

If the explosion were spherical, I think that electron scattering of light would polarize in a random direction, therefore the net polarization would be 0. At the relativistic speeds present in a supernova, this would be Compton scattering, which I think is what the hint is suggesting.

Follow-up 2: How is polarization observed in the radio? How about at optical wavelengths?

In radio, antennas are polarized to dissect radiation into one of the four Stokes parameters which tells you how light is polarized.

In the optical, some filters will only let in certain polarizations, so filters can be used to detect which way light is polarized.

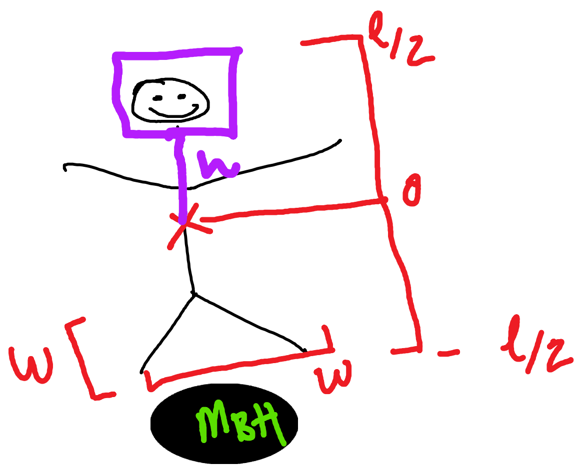
(17) What's the minimum mass of a black hole for which you could survive a fall through the event horizon without being ripped apart? (Assume 1 ton tensile strength.) How does this relate to the BH mass range for which we expect tidal disruption flares caused by shredding main-sequence stars?

From first principles, $dF = a\ dm$.

This can be thought of as the amount of force your muscles will need to act to keep your head (or some other part of you) from separating from the rest of your body. The acceleration then is how fast that body part is moving away from the rest of the body.

$$a = -GM_{BH}\left(\frac{1}{(r+h)^2} - \frac{1}{r^2}\right) \approx \frac{2GM_{BH}h}{r^3}$$

Let's assume that you are rectangle-shaped,
with the width and depth being equal.



$$dm = \rho dV$$

$$\rho = \frac{m}{lw^2}$$

$$dV = Adh = w^2 dh$$

Summing up all the components of you

$$F = \int_0^{l/2} a\ dm$$

Plugging a and dm in gives

$$F = \frac{GM_{BH}ml}{4r^3}$$

We'll set the radius equal to the Schwarzschild radius. $r = R_S = \frac{2GM}{c^2}$

Fun fact: a few days ago I was talking to my friend who speaks German about this question, and he told me Schwarzschild means "Black Shield" in German. I looked it up and it seems to be true which is pretty neat.

Plugging in this radius and solving for the mass of the black hole gives

$$M_{BH} = \frac{c^3}{G}\sqrt{\frac{l\,m}{32\,F}}$$

Assuming a 1 ton tensile strength, means 10,000 newtons of Force, this will give you a minimum mass between 3000 and 5000 $M_\odot$ depending on your mass and height.

This only considers the longitudinal force of you being spaghettified at the event horizon. In my notes I also calculated the compressive force around the sides of you and got a result for a minimum mass of black hole around 1000 $M_\odot$.

I wonder, if you were presented with an event horizon, turning yourself sideways could increase your survival chance (through the event horizon, at least).

For the second part of this question, it doesn't make a ton of sense to talk about the tensile strength of Hydrogen/Helium gas.

The simple way to think about this is by equating the force of gravity to the tidal force. When the tidal force is stronger than the force of gravity holding the star together, it will become disrupted. In reality it will become disrupted even sooner because the star will feel perturbations before it reaches this point, but a careful job seems to only change things by less than a factor of two.

For an order of magnitude:

$F_g < F_T$

$\frac{GM}{R^2} < \frac{2GM_{BH}R}{r^3}$

$\frac{M}{M_{BH}} < 2\left(\frac{R}{r}\right)^3$ This is also known as the Roche Limit.

Again setting $r = R_s$ and solving for M_{BH} you get something on the order of 10^{8-9} depending on the mass and radius of the main sequence star.

With tides, it seems that the important thing to consider is the mass ratio of the two objects. When the mass ratio was extremely large (person vs black hole) the survivable event horizon was an order of 10^3 and above. For the less extreme mass ratio of star vs black hole, this is true only of 100 million mass black holes.

Follow-up 1: "Tidal tails" sometimes form around small galaxies or globular clusters in orbit around a larger galaxy. Why and how does this occur?

This occurs because of tidal forces between the small and large galaxy. Following the logic of tidal forces on people and stars, the larger galaxy will disrupt the smaller galaxy if the smaller galaxy comes within some radius of the larger galaxy.

Follow-up 2: A star is on a parabolic (zero-energy) orbit, before it is disrupted by passing too close to a black hole. What do you expect to happen to the debris? (Hint: think about different parts of the star. Assume it is not too close to the BH, so relativistic effects are not important.)

I'm not sure what exactly is meant by debris. The star could be losing mass due either to normal wind mass loss rates or induced mass loss from perturbations caused by tidal forces that aren't enough to entirely disrupt the star but could cause pulsations, possibly even eruptive ones.

That mass would be accreted onto the black hole, it would form a disk around it, the material would be very hot and have high velocities. You'd expect to see x-ray emission from the thermal component and radio emission from synchrotron radiation.

Hi Bethany,
Your physics exam went very well.

Planet detection: your answer was excellent. The only small issue is that in the follow-up on biases of different detection methods you didn't focus on some of the actual biases, like being more sensitive to close-in planets in the transit method, or needing to have more than one transit in the duration of the experiment to know for sure that a transit has occurred.

Polarization: Your initial answer is good. For the follow-up about a supernova, you weren't familiar with the fact that electron scattering in the photosphere of the SN makes it linearly polarized around the limb, just like the Sun is, so that an elliptical image of the explosion (which ight occur for an aspherical explosion) leads to a net linear polarization. For the follow-up about detection, your answer is correct although it doesn't cover how you might observe circular polarization in the optical. It would be useful to understand how this works in practice, perhaps using 3D movie glasses (which select for right and left circular polarization) as an example.

Tidal disruption: your answer here is excellent. The follow-up on tidal tails went well. For the follow-up on stellar TDEs, you didn't make the connection between what happens to a distrupted star and the tidal tails that form around globulars or galaxies -- it's the same phenomenon.   Just because TDEs are an interesting laboratory for dynamics, accretion, etc., it may be a good idea to review how this is thought to happen and what is actually observed.

Best,
Chris