Special lecture: tidal disruption events

Initial question: What can radiative processes tell us about tidal disruptions of stars by massive black holes?

The time-variable universe is exciting because it can tell us about fast motion and violent events. One category of time-variable events that is near and dear to the hearts of Marylanders such as Suvi Gezari and Brad Cenko is tidal disruption events. In this class we will start with some basics about these events, then lay before you some clues about their nature. This is a hot topic with many unknowns, so you have the prospect of contributing some ideas. You can think of this class as a series of group questions, where I will try to get you to come up with various ideas along the way.

Let's begin with the process of disruption itself. Suppose that you have a uniform-density star of mass m and radius R that passes in a nearly-parabolic orbit of pericenter distance r_p from a massive black hole of mass M. If we assume that $R \ll r_p$, then the tidal force due to the black hole across the stellar radius is

$$f_{\rm tide} \approx \frac{2GMmR}{r_p^3}\ . \tag{1}$$

The self-force of the star is $f_{\rm self} \approx Gm^2/R^2$. Equating the two gives $f_{\rm tide} = f_{\rm self}$ if

$$r_p \approx r_{\rm tide} \approx (2M/m)^{1/3} R\ . \tag{2}$$

Thus although the factor of 2 won't apply to all sources, we basically figure that when $r_p < r_{\rm tide}$ for uniform-density stars, the star will be destroyed. Note that another way of phrasing this is that the orbital frequency at the tidal radius, which scales as $(M/r_{\rm tide}^3)^{1/2}$, is proportional to the square root of the average density of the star, $(\bar\rho)^{1/2} \propto (m/R^3)^{1/2}$. Thus the orbital frequency at disruption does *not* depend on the mass of the black hole; this simplifies things but also removes possible information about the system.

In this Newtonian limit, and as before assuming that the star was basically on a parabolic orbit (meaning that its total orbital energy was zero), about half of the star's remains will be ejected from the system and about half will be bound more tightly. The more bound matter could accrete onto the black hole, although there is a prospect that shocks from returning material could unbind some more of the matter.

In a paper by Martin Rees (my grandadvisor) in 1988, which was corrected in 1989 by Sterl Phinney (my advisor), there is an argument made about the time dependence of the accretion rate of the returning matter. We note that the accretion rate dm/dt can be written $dm/dt = (dm/de)(de/dt)$. Here e is the specific energy of the matter; note that "specific" in this context always means "per unit mass". Now, the specific energy of a

Keplerian orbit is

$$e = -\frac{GM}{2a} \; , \tag{3}$$

where a is the semimajor axis. In addition, we know from Kepler's third law that the orbital period is $t = 2\pi(a^3/GM)^{1/2}$, so $a = [GM(t/2\pi)^2]^{1/3} \propto t^{2/3}$. This means that $e \propto t^{-2/3}$, so $de/dt \propto t^{-5/3}$. Rees and Phinney made the approximation that the distribution of the mass of the disrupted remnant with specific energy is flat ($dm/de = \text{const}$), which means that we get the classic result

$$dm/dt \propto t^{-5/3} \; . \tag{4}$$

Sharp onsets of emission from a source, followed by a $t^{-5/3}$ decay, are considered signatures of possible tidal disruption.

According to Rees (1988), when $M \gg m$ the most bound debris will have a specific energy

$$e_{\rm min} \approx -(M/m)^{1/3}(Gm/R) \; . \tag{5}$$

The specific binding energy of a circular orbit at $r_{\rm tide}$ is

$$e_{\rm tide} \approx -GM/(2r_{\rm tide}) \sim (M/m)^{2/3}Gm/R \sim (M/m)^{1/3}e_{\rm min} \tag{6}$$

(note that we have dropped factors of 2). Thus the semimajor axis of the most bound orbit is $\sim (M/m)^{1/3}$ times the tidal radius. For a supermassive black hole of mass $10^6\ M_\odot$ and a star of mass $1\ M_\odot$, this semimajor axis is thus ~ 100 times the tidal radius. This means that the characteristic first return time is $\sim 100^{3/2} = 1000$ times the orbital period at the tidal radius, which as we discussed before is $\sim (G\bar{\rho})^{-1/2}$ where $\bar{\rho}$ is the average density of the star. What is this time?

Some early predictions for the spectra assumed that the radiation would be at the Eddington luminosity and would be emitted as a blackbody from a sphere of radius $r_{\rm tidal}$ (well, not exactly; they used a multitemperature disk, but we'll simplify to a blackbody). What is the predicted temperature for a $10^6\ M_\odot$ supermassive black hole?

Actual temperatures seen in X-ray detected tidal disruption events are $\sim 10^6$ K, and in optical and UV detected tidal disruption events are maybe a few times 10^4 K. Each of those temperatures might be considered surprising in their own way; what do they imply about the sources?

An especially interesting tidal disruption event was seen with the Swift satellite in 2011. Burrows et al. and Zauderer et al. (Ashley Zauderer was a Ph.D. student at Maryland!) discovered, respectively, an X-ray flux of up to about 10^{-8} erg cm^{-2} s^{-1} and a peak radio flux (at 6×10^{11} Hz of 80 mJy (remember that a Jansky is 10^{-23} erg cm^{-2} s^{-1} Hz^{-1}). The radio spectrum at low frequencies rises with a slope that (corresponding to our previous discussions) is $\nu F_\nu \propto \nu^{2.3\pm 0.1}$. Various observations showed that the source is at a redshift of 0.354. What does this imply about the X-ray and radio luminosity? What do those luminosities and the slope of the radio spectrum imply about the source?

Overall, what do these data have to say about tidal disruptions? Sometimes the power law decays do not follow $t^{-5/3}$ well; should we abandon the basic physical mechanism (i.e., should we say that these events are not tidal disruptions but are something else instead), or is there enough freedom in the models to accommodate such differences? Are there good prospects for using these observations to learn about black holes in the centers of galaxies? Do you think we will have a reasonable chance to see effects specifically related to general relativity (e.g., precession of orbits or orbital planes)?