Massive Black Hole Growth and Formation

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Abstract. I review current difficulties in understanding the origin of the supermassive black holes we now think reside in almost all normal to large galaxies. For example, it is not obvious how so much matter can be rapidly packed into such a small volume so as to produce the accreting supermassive black holes observed out to redshifts $z > 6$, when the Universe less than a tenth of its current age. I then discuss possible solutions to some of these difficulties. Of interest to this conference, I will try to shed some light (not very successfully) on whether these black holes reach their current masses mainly by the accretion of gas or by the merger and coalescence of smaller black holes.

OVERVIEW

The existence of the quasar phenomenon poses two fundamental questions to astrophysics. The first is how energy can be extracted so efficiently from so small a volume to produce emission that can greatly outshine the entire galaxy that hosts the quasar. Although we do not completely understand the details, e.g., the accretion disk physics, we think the answer likely involves the presence of a black hole, with a mass $\gtrsim 10^9 \mathrm{M}_\odot$ in the most extreme cases. The inferred existence of such an object, a supermassive black-hole, poses the second fundamental challenge and the topic of this contribution. I will now briefly run the main difficulties in understanding the formation of supermassive black holes is difficult.

In our current understanding of inflation, a quantum fluctation involving such a large mass scale is extremely unlikely. Such a black hole must therefore have been created by more traditional astrophysical means. At first, this might not seem that hard. We know already, for example, that black holes can be formed in the collapse of a stellar core that occurs when a massive star exhausts its nuclear fuel. If we take such a black hole and drop it into a billion solar masses of gas, as often found in the centers of galaxies containing powerful quasars, the black hole will eventually swallow all the gas up, or so the story goes. A first complication to this story is that in the standard lore, a black hole cannot accrete faster than the Eddington mass accretion rate (the rate at which the radiation pressure from the hot infalling matter is so large that it overcomes the force of gravity). This critical accretion rate is proportional to the mass of the accreting object, which implies that the mass of an object that is growing at the maximal (Eddington) accretion grows exponentially on a timescale known as the Salpeter time,

$$t_{Sal} = \frac{\varepsilon \sigma_T c}{4\pi G m_p} \approx 45 \varepsilon_{0.1} 10^6 \text{ years,} \tag{1}$$

where m_p is the mass of the proton, σ_T is the Thomson cross-section, and $\varepsilon_{0.1}$ is the efficiency at which accreting gas rest mass energy is converted in radiation expressed in units of 10%, the standard value for an accreting Schwarzchild black hole. (In terms of this efficiency, the accretion luminosity is $L_{acc} = \varepsilon \dot{M}_{BH} c^2$, where $\dot{M}_{BH}$ is the black hole accretion rate. A good overview of black hole/quasar phenomenology may be found in the 1990 Saas Fee Lectures.) Exponential growth might seem sufficiently rapid, but the Sloan Digital Sky Survey has now found quasars at redshifts $\gtrsim 6.4$ ([1]), when the universe was less than a billion years old. If we start a black hole out with a mass typical of known stellar mass black holes, $\sim 5-30 \mathrm{M}_{\odot}$, at best we marginally have enough e-folding (Salpeter) times to build up the black hole. It is also worth noting that the spectra of high redshift quasars do not appear particularly young in the sense that the inferred abundances of metals in the gas surrounding the quasar are similar to those found in low-redshift quasars, which are *greater* than solar. This is surprising because we think metals are produced by supernovae, and such high abundances therefore imply many generations of star formation-supernova cycles – more than occurred during the entire $\sim$ 10 billion year lifetime of our galaxy. In other words, not only the black hole, but everything around it, must evolve incredibly fast compared to conventional cosmic timescale. The problem only becomes worse if one thinks (see below) that the main, or at luminous, accretion phase of a quasar lasts only for a time $t_{acc} \sim t_{Sal}$.

There are two main classes of proposed solutions. First, one can simply abandon the Eddington limit. The limit might not be relevant because the assumptions that go into it (e.g., e.g., spherical symmetry) are not valid in real life, or simply because black holes instead gain their mass mainly by by the merger of smaller black holes in a process that does not involve significant (non-gravitational) radiation. Second, one can minimize the required number of mass e-foldings by starting out with an object, the so-called “seed," that is already quite massive ($\sim 10^3 - 10^6 \mathrm{M}_{\odot}$) and collapses directly into a black hole (e.g., see the contribution by Shapiro in this proceedings). I will discuss these possibilities in more detail in following sections. They may all turn out to be relevant.

Even if we explain away the rapid growth of these black holes, Nature has more puzzles for us. Another major but often skipped complication is that a lot of gas packed into a small space usually does not sit quietly waiting to be accreted. If the gas is self-gravitating (i.e., $M_{gas} \gg M_{BH}$, as it might be during the initial phases of black hole formation) and can cool rapidly (as it will when it contains dust and metals), it becomes gravitationally unstable and quickly fragments, forming stars. The energy release from these stars and the supernovae that follow can be quite substantial. In objects known as “Ultraluminous Infrared Galaxies” (ULIGS; see review by [2]), usually merging galaxies where a large amount of gas has been driven into one region by the gravitational torques of the encounter, the inferred nuclear star formation luminosities are enormous, comparable to or even exceeding the luminosity of the hidden quasars that often lurk in these objects. (The binary quasar galaxy NGC 6240 is an example of such a system.) Such strong star formation is known to drive strong winds and outflows from galaxies ([3]), so it is not entirely obvious if and how much of this gas would end up in a black hole.

The heat and radiation released by star formation is an example of the “feedback" that gas exerts in a gravitationally collapsing system and constitutes a (very significant) theoretical bottleneck in our understanding the structure we see around us. I note that the radiation and kinetic power in matter outflows (winds and jets) produced by a black hole accreting at or above the Eddington limit is perhaps the ultimate example of feedback. This feedback could be so strong that some (e.g., [4]) speculate that once the accreting black hole gets too big and bright, it blows out all the gas in the center of its host galaxy, shutting down both the accretion onto the black hole and any surrounding star formation that might be going on. I therefore expect that we will not have a full understanding of black hole growth until we overcome the feedback problem and can simulate the environment not just near the black hole event horizon but on galaxy scales too. I note (see below) that the presence of gas and feedback can influence not just the fate of a single black hole but also the evolution of a pair of black holes that are trying to merge, another of the possible pieces in massive black hole formation puzzle. In other words, the development of our theoretical understanding is still in its early stages.

Observers are never to content to wait for theorists, however, and have tried to solve the feedback problem for them by correlating the observed properties of quasar host galaxies and sometimes even those of ordinary galaxies with those of quasars. Over the years, an increasingly profound connection has emerged. For example, most quasars seem to reside in interacting or merging systems of galaxies. These are the same types of galaxy that often show spectacular star formation rates, and as noted, when one looks hard enough (e.g., using hard X-rays that can penetrate very large columns of dusty gas) one often finds evidence for an accreting black hole, or a pair of them in the case of NGC 6240 (see the contribution by Komossa, this proceedings). Similarly, a closer look at the spectra of quasars finds evidence for significant contamination by star formation light, particularly if one selects quasars by a technique (e.g., [5]) that is not biased against finding quasars shrouded by dust and gas (which is almost always present when star formation is strong). Quasar activity, star formation, and galaxy mergers therefore seem to be highly interrelated phenomena.

Given that galaxies containing bright quasars are rare compared to ordinary galaxies, one might (and did) treat this fact as a curiousity of not much practical importance. However, because the structure we see around formed in a hirearchal fashion, *every* galaxy we see today has been the product of many mergers. The question then becomes does every galaxy have a quasar (a bright, actively accreting black hole) inside it? The answer is clearly no since quasars are always relatively rare, even at high redshifts when mergers are common. Curiously, however, if one plots the evolution of blue (star formation) light in the universe as a function of redshift, the evolution is very similar to that of the quasar number density. We now realize that surveys based on blue/ultraviolet light have missed a large fraction of the merger-induced star formation activity in the Universe due to the gas and dust obscuration that usually accompanies violent star formation. At the same time, we have also realized that obscuration by dust and gas probably has also caused us to miss many quasars (see contribution by Comastri, this proceedings). Although the definitive answer will have to await the launch of SIRTF (a far infrared telescope sensitive to the re-emission of absorbed star light by dust), the star formation rates corrected for dust obscuration seem to agree again with quasar densities found by satellites like Chandra that have better hard X-ray sensitivity (and thus are less affected by obscuring gas). A simple hypothesis that explains why star formation and quasar activity track each other so well and resolves the the discrepancy in the relative numbers of quasars and galaxies is that (a) every galaxy goes through a quasar phase, and (b) the quasar phase probably occurs during the merger-induced phase of intense star formation activity and both these phases are very short-lived.

SIRTF should answer whether part (b) of the last hypothesis is correct, but a corollary of part (a) already appears to have been verified. Namely, if every galaxy passes through a quasar phase, then every galaxy must harbor a massive black hole even if it is no longer visible as a quasar because accretion onto the black hole has stopped. A few years ago, Richstone and others (see his contribution, this proceedings) set out to find evidence for “dead" black holes by systematically studying the dynamics of stars and gas in the nuclei of galaxies. In essentially every case where their instrumental resolution would have allowed them to detect a supermassive black hole, they have found one. Even more amazing is the discovery of the so-called $M-\sigma$ relation where the inferred mass of the black hole (M) correlates tightly with the velocity dispersion (σ) of the gas and stars far away from the black hole (where the black hole’s gravity is dominated by that from other stars and gas in the galaxy) and, to a lesser extent, to the total amount of stars in the bulge of the galaxy. In other words, the black hole and the stars somehow know about each other intimately, i.e., their formation processes are highly interrelated as might be expected due to feedback, for example. The depth of the gravitational potential well at the center of the merger, measured by the dispersion σ, might determine how much star formation and quasar activity can be supported there before the gas needed to power the star formation and the quasars is unbound. Alternatively, σ might simply provide a more accurate measure of the gas density in the vicinity of the black hole, and for some unknown reason a fixed fraction of the available gas always ends up in stars compared to the black hole. The explanation of the $M-\sigma$ relation is currently a topic of lively debate and undoubtedly will play an important role in ultimately understanding how massive black holes grow.

The likely connection between quasars and merger activity of galaxies also suggests that the mergers of smaller black holes might indeed be an important ingredient in the formation of massive black holes. One can concoct scenarios, for example, where the the amount of gas accreted during a quasar phase is in fact not that large. Rather at very early times, when the typical systems were much smaller and simpler, some fundamental star formation process, e.g., related to the physics of population III star formation (see below), determined the fraction of gas that ended up in stars and eventually black hole remnants. If this fraction were relatively universal and black holes always merged efficiently when their host systems merged, then the ratio of black hole mass to the mass in stars and/or gas would be preserved, explaining the $M-\sigma$ relation without any feedback effects. For more on the role of black hole mergers in massive black hole growth, see the contributions by Haehnelt and Volonteri.

One possible problem with such scenarios is the observed tightness of the $M-\sigma$ relation, which might not survive the effects of repeated mergers. Currently, though, the hypothesis of significant growth by mergers and actually any growth mechanism that does not radiate efficiently (such as slow black hole growth via a low radiative efficiency accretion solution like an ADAF, e.g., see [6]) face a much more severe problem. This important argument comes from a comparison of the total energy radiated by known quasars to the total mass we think exists in relict black holes.

As cleverly noted by Soltan([7]), if we think we understand black hole accretion physics and the accretion luminosity is given by a formula such $L_{acc} = \varepsilon \dot{M}_{BH} c^2$, then we can invert the observed luminosity and redshift distribution of quasars to obtain their corresponding distribution of instantaneous mass accretion rates, $\dot{M}_{BH}$, as a function of redshift and luminosity. Integrating this distribution of accretion rates over all quasar luminosities and over time (redshift), we obtain the total amount of matter that must have been accreted by the quasar black holes. Skipping details (see also [8], [9], [10] for more recent attempts at this calculation), the end result can be expressed as a local mass density of accreted matter, which the most recent evaluation, e.g., [10], gives as

$$\rho_{acc}(z=0) = 2.1\times10^5(C_B/11.8)[0.1(1-\varepsilon)/\varepsilon]\mathrm{M}_\odot\mathrm{Mpc}^{-3}. \tag{2}$$

As already noted by Soltan (who obtained a somewhat lower number because the optical quasar luminosity function was not so well-known at the time), this number is actually quite large. The typical density of galaxies like our Milky Way is roughly $1 \sim \mathrm{Mpc}^{-3}$, which means that even if every galaxy has a black hole, the typical black hole must still be fairly massive ($\gtrsim 10^5\mathrm{M}_\odot$; our galaxy in fact has a black hole of $\sim 3\times10^6\mathrm{M}_\odot$). If fewer galaxies contain blackholes, then their black holes must of course be that much much more massive. Moreover, because it is quite possible that surveys have missed quasars and because accretion or mergers might not result in optical radiation, the mass density estimate is a lower limit on the mass density of the relict black holes we should find in galaxies today. This assumes, of course, that black holes are not ejected into intergalactic space during merger events (but see the contribution of Volonteri).

With such an estimate in hand, one can immediately compare it to relict mass estimate obtained using the $M-\sigma$ relation and the distribution of galaxy velocity dispersions that have become available using recent galaxy surveys like the Sloan survey. (See the contribution by Richstone, [10], and [11] for much more discussion of how this is done.) Initial estimates of the local relict black hole mass density inferred using a related but poorer black hole mass-bulge luminosity relation gave a density ~ 5 times higher that from the Soltan estimate, in other words it seemed that massive black holes have gained their most of their mass in an invisible way. (Hence the spate of papers on this topic in the late 1990s.) Recent estimates that corrected for prior systematic errors and use the better $M-\sigma$, however, now give a value

$$\rho_{M-\sigma} \approx 2.5\times10^5\mathrm{M}_\odot\mathrm{Mpc}^{-3} \tag{3}$$

for a Hubble constant of 65 $\mathrm{km\,sec^{-1}\,Mpc^{-1}}$, which agrees suprisingly well with the Soltan-type estimate.

Some have expressed happiness with this result and consider it a confirmation of our overall understanding, but I think considerable caution is still advisable, e.g., see [10] for a discussion of some of the possible problems with and surprising conclusions from these estimates. In particular, while the $M-\sigma$ estimate seems to be on relatively good footing now, the Soltan-type estimate is not. In the expression for ρ_{acc} above, there is still a large factor of uncertainty in the bolometric correction C_B that should be applied to optical samples (quasars radiate only a small fraction of their power in optical waveband). The efficiency ε, of course, is still largely a theoretical and arbitray quantity. More importantly, it is now clear that optical samples have missed many obscured quasars, which have their own sets of (not yet well-determined) bolometric corrections. Recent Soltan-type estimates based on the X-ray and infrared backgrounds (see Comastri, this proceedings) tend to give significantly higher mass density values than optically-based estimates, $\sim 6-9\times 10^5 \mathrm{M}_\odot \mathrm{Mpc}^{-3}$ (e.g., [12], [13], Comastri, this proceedings). If these new estimates are in fact more accurate, we now have to deal with problematic details such as source efficiencies $\varepsilon > 0.36$, the maximum value obtained in the case of a maximally rotating Kerr black hole. (On the other hand, while such a high efficiency should not occur in the standard picture, see the section below on the Eddington limit.) As discussed by Comastri, a possible resolution to some of these problems comes from noting that although the Soltan argument is independent of cosmological parameters such as the Hubble constant, it is not independent of the redshift distribution of the sources. [The higher the typical redshift $\bar{z}$ of a quasars, the higher the inferred local mass density by a factor $(1+\bar{z})$.] Although all the evidence is not in yet, the peak of the redshift distribution of hard Chandra X-ray sources now seems to be $\bar{z}\sim 1$ instead of $\bar{z}\sim 2$ for optical quasars, which might bring the X-ray estimates at least into better agreement with the $M-\sigma$ estimates. (Why $\bar{z}$ from X-rays should be so low, however, is yet another interesting question.) Eventually the comparison between the Soltan and $M-\sigma$ type estimates should prove a powerful constraint on black hole accretion and growth models, but it is not quite there yet.

In the remainder of this contribution, I will focus in more detail on a few of the specific issues discussed above as well as some of the lessons we can learn from primordial and present-day star formation.

THE VALIDITY OF THE EDDINGTON LIMIT

If black holes need to accrete their mass very rapidly, it is not at all impossible theoretically that they can be “force fed" at rates greater than Eddington limit. As discussed, e.g., in [14], if there is amount sufficient of accreting gas, photons can actually be trapped by the optically thick gas and simply advected into the black hole along with the matter. The result is fast accretion but with a low radiative efficiency.

If this low radiative efficiency is problematic in light of the recent Soltan/, $M-\sigma$ comparison, it is still may be possible to accrete rapidly and radiate at a super-Eddington rate. The Eddington limit is based on the assumption that the radiation field due to the hot accreting matter has spherical symmetry so that all matter at a given distance from the black hole seems the same, full radiation force. In real life, however, the radiation field could become quite anisotropic, with the radiation from the hot accreting matter escaping to the observer along low gas density/optically thin channels while the accreting matter falling into the black hole flows in along high gas density/optically thick channels (where it is shielded from the radiation field). In this case, the formal Eddington limit could be significantly exceeded, e.g. see [15]. As also discussed there, note that matter which has fallen down a sizeable portion of the gravitational potential of the black hole need not inevitably end up in the black hole, e.g., if it is deflected by a strong radiation field and forms an outflow. In this case, the overall efficiency of energy extraction will be less than the maximal value since all particles do not make it in to the event horizon. Here, we are defining defined efficiency to be the kinetic energy gained (and presumably eventually radiated) by *all* particles that initially started falling towards the black hole divided by their rest mass energy. Note, though, that this is *not* the same as the efficiency parameter ε used in a Soltan-type argument. This efficiency is in practice determined by taking the amount of energy that is observed to be radiated by the source in a given amount of time and dividing it by the rest mass energy of only those partices that actually crossed the event horizon during that time. Since we are not counting all the particles initially in the accretion flow, this quantity can actually be *greater* than the maximal value.

SOME LESSONS FROM PRESENT-DAY STAR FORMATION

The formation of a star is the one of the possible endpoints of the gravitational instability of gas as is probably the formation of massive black hole. It is not surprising then that the formation of stars, particularly that of massive stars, might have some close connections and parallels to massive black hole formation. (Observationally, the connection between starbursts and quasar activity certainly seems to indicate this.)

One lesson from present-day star formation is that building up massive objects is certainly possible despite various theoretical objections. For example, stars above 10 $M_{\odot}$ radiate near the Eddington limit and therefore should not accrete significantly and grow beyond this mass, yet 100 $M_{\odot}$ stars certainly exist. Because massive stars often tend to be near others, hierarchical merging of many small stars to form a few large ones may be involved, as it might be with black holes. Although large-scale star formation simulations are not sophisticated enough yet to include stellar radiation (nor magnetic fields), the current hydrodynamical simulations such as [16] show that this process indeed occurs, although they show that other processes may be important. For example, if we simply ignore the Eddington limit (e.g., because in real life the inflow is anisotropic) and allow bound, infalling gas to accrete on a protostar, accretion can become very significant, very fast. Inhomogeneities in the surrounding gas, sometimes caused by close encounters with other protostars, cause gravitational torques to be exerted on infalling gas that causes it to lose much of its angular momentum very quickly without relying on the gas viscosity in an accretion disk. The mass gained by accretion can be comparable to or exceed the masss gained by mergers. Also, very interestingly, if one has a clump of protostars and for some reason, one of the protostars gains a bit more mass, “competitive” accretion occurs and more gas ends up on the the heavier protostar than on the other protostars, i.e., the massive get more massive. Moreover, while protostars can be ejected from the clump (a worry for those studying the evolution of a cluster of black holes), the most massive object instead tends to sink to the center of the clump and happily continues to swallow up gas and eventually stars that get too close. This is exactly the kind of scenario one needs to take a black hole seed and make it grow quickly. The ingredient that appears to make everything work in the star formation case, and that has not been well-treated yet in most numerical studies of black hole growth, is the presence of a large amount of collisional, dissipative gas. Although they are too simple, the latest simulations are looking increasingly like reality, so there may be something to them, i.e., magnetic and radiation effects that might have been important, may not be that important in practice.

One other lesson worth bearing in mind is that despite theoretical thinking to the contrary (e.g., that says protostellar accretion must proceed slowly via ambipolar diffusion), star formation appears to proceed very quickly. The molecular clouds which form stars in our galaxy are now though to persist for only a few million years before being shredded by turbulence, so whatever stars formed must have done so on this short timescale. Indeed, galaxies can sustain very high star formation and gas consumption rates that would be impossible if star formation were slow. Observationally, the timescale of relevance to a massive, gas-rich starbursts (and in hydrodynamical simulations of star formation) is the dynamical (gravitational free-fall) timescale of the central gas distribution. In galactic nuclei, these timescales can be very short compared to cosmological timescales, on the other order of tens to hundreds of millions of years (and interesting, comparable to the black hole Salpeter time!). If black hole formation and growth is but an extension of extreme star formation, then it is may not be so surprising to metal-rich quasars even at redshifts ~ 6.

BLACK HOLE SEEDS FROM PRIMORDIAL STAR FORMATION?

As shown, for example, in the numerical simulations of [17] and [18], the formation of the first ("Population III") stars might have proceeded rather differently from that of present-day stars. The key difference is that, by definition, primordial gas has not been polluted yet by the dust and metals that are produced by stars. Primordial gas therefore lacks the main coolants that regulate present-day star formation, and if it is to collapse, it must first cool by relying on the much slower process of molecular hydrogen cooling (the dominant coolant below a temperature of 10^4 degrees when metals are not present). The lowest energy level of molecular hydrogen and the transition from NLTE to LTE cooling set characteristic temperature and density scales for cooled gas of $T \sim 300$ K and $n \sim 10^3 \mathrm{cm}^{-3}$ respectively. Cooling becomes even more inefficient for lower temperatures and higher densities and gas tends to sit at these values for a long time.

When such characteristic temperature and density values exist, the gas will fragment gravitationally down to clump scales of order the Jeans mass ($\propto T^{3/2} n^{-1/2} \sim 1000 \mathrm{M}_\odot$) appropriate for this temperature and density. Eventually, the clumps will collapse as the gas (slowly) cools further, but by then pressure forces have erase most density fluctuations, and contrary to speculation, no further sub-fragmentation occurs, except perhaps to split the clump into a binary if its angular momentum is high. In other words, gravitational instability in primordial gas tends to produce bound, collapsing clumps of gas of chararacteristic mass $\sim 1000 \mathrm{M}_\odot$. How much of the mass in the clump eventually ends up in a star is an open question, but a new high-resolution, hydrodynamical calculation by Bromm that follows accretion from outer parts of the clump onto a sink particle (the protostar) at the center shows that much of the clump mass ($\sim 300 - 700 \mathrm{M}_\odot$) could accrete onto a central protostar before massive star that forms goes supernova (on a timescale $\sim 3 \times 10^6$ years). Simulations which simplify the hydrodynamics by assuming spherical symmetry but treat radiation transfer correctly (e.g., [20]) reach a similar conclusion. In other words, the first generation of stars could have been very massive and could have produced comparably massive black hole remnants. (See the contributions by Fryer and Shapiro for a discussion of the fate of massive, primordial stars.) These could well be the seeds for massive black hole growth, e.g., see Volonteri (this proceedings). The merger of these primordial black holes might be an important signal for LISA and might provide some of the intermediate black holes that have been discussed at this meeting (see contributions by Miller, Van der Marel, and Mushotzky).

Molecular hydrogen is very fragile and easily destroyed by ionizing radiation, e.g., from a first generation of massive stars. It may not be impossible, then, to find lower density regions of primordial gas that have only started to collapse and have neither molecular hydrogen and little or no metals. Exactly how much primordial gas meets these requirements is not yet clear, but it is interesting to see what the fate of such a gas cloud would be. Without significant metals and molecular hydrogen, one must rely on atomic hydrogen cooling and the relevant Jeans mass scales jumps signicantly. Bromm and Loeb ([19]) have recently carried out a collapse simulation which shows the the runaway collapse of one or two objects (depending on the initial gas angular momentum) with masses $\sim 10^6 M_\odot$. Such massive objects would collapse directly into a black hole and would never form a star. In other words, primordial star formation might occasionally produce very massive seeds indeed!

GAS AND BLACK HOLE MERGERS

As discussed by Milosavjlevic (this proceedings), it is not clear whether the central black holes of two merging galaxies will also merge. If only stars are present at the center of the merged galaxy, the hardening black hole binary will eventually eject all of them, "depleting its loss cone," and stopping the merger. This result may apply to the merger of gas-poor galaxies today, but in the gas-rich mergers of the past, e.g., the ones that produce quasars, the situation may be quite different. Gas is collisional and dissipative and therefore cannot be easily ejected, especially if it is present in large quantities, as in an early merger. Fig. 1 shows the result of an idealized calculation by Andres Escala where two black holes are dropped into an isothermal sphere of hot gas with 10 times the mass of the black holes. Low-angular momentum gas is always present inside a merging black hole binary, causing a continued gravitational drag that will cause the binary to quickly harden to the point where gravitational radiation takes over.

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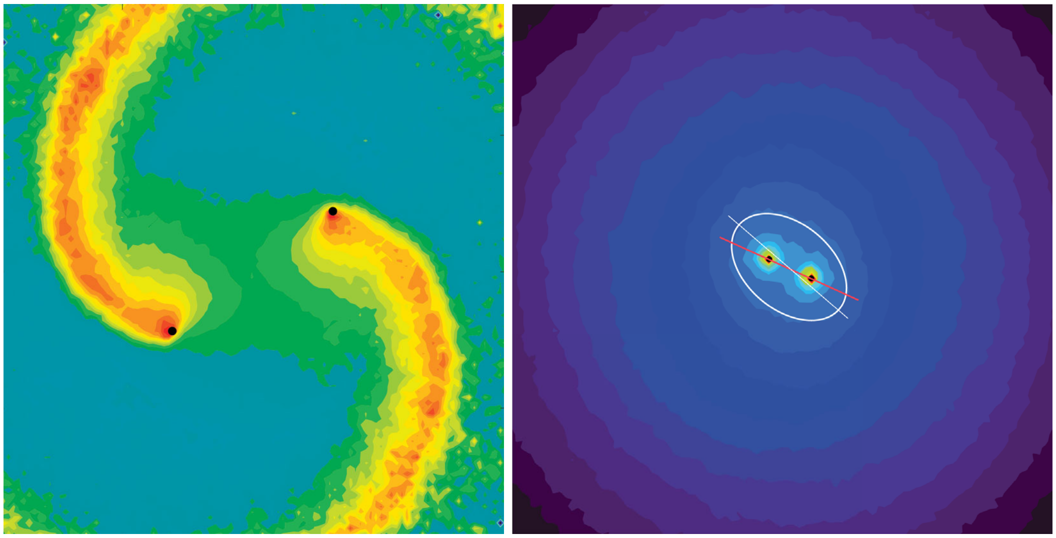

FIGURE 1. Gas density plots showing evolution of black hole binary in a massive gas sphere. Initially (left panel), the black holes form density wakes behind them and standard dynamical friction causes the holes to spiral in. Once a hard binary forms (right panel), gas is still present near the black holes and has an ellipsoidal density configuration that always lags the binary, exerting a torque on the binary and causing it to harden further.

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