"Dead Quasars" in Nearby Galaxies?

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The nuclei of some galaxies undergo violent activity, quasars being the most extreme instances of this phenomenon. Such activity is probably short-lived compared to galactic lifetimes, and was most prevalent when the universe was only about one-fifth of its present age. A massive black hole seems the inevitable end point of such activity, and dead quasars should greatly outnumber active ones. In recent years, studies of stellar motions in the cores of several nearby galaxies indicate the presence of central dark masses which could be black holes. This article discusses how such evidence might be corroborated, and the potential implications for our understanding of active galaxies and black holes.

It has been known for more than 25 years (*1*) that galaxies are more than just assemblages of stars and gas: some have a bright central "nucleus," whose emission does not come from normal stars. The most extreme "active galactic nuclei" (AGNs) are the quasars, where a central object no bigger than our solar system far outshines all the 10^{11} stars in its host galaxy.

How AGNs form and evolve is still, in many respects, mysterious. However, one of the few things about which there is a consensus is that the activity is powered primarily by *gravity*: in the centers of some galaxies, stars and gas become so close-packed that some kind of runaway catastrophe is triggered. Violent activity is a relatively short-lived phase in the life of a galaxy, and involves the growth of a black hole with the mass of millions, or even billions, of suns. "Dead quasars"—massive black holes now starved of fuel, and therefore quiescent—should be more common than active quasars and are now being discovered in nearby galaxies. These objects can provide clues to the enigma of quasars, as well as being interesting in their own right.

Clues from Quasar Demography

Quasar activity seems to have peaked sharply at redshift $z \simeq 2$, when the universe had about one third its present scale (2 to 3 billion years after the Big Bang). Astronomers have found it much harder to discover quasars with still larger redshifts. This is only partly the effect of greater distance: at larger redshifts the quasar population genuinely thins out. However, there are at least a few quasars with redshifts $z \gtrsim 4.5$: when the universe was no more than a billion years old, some galaxies must have formed, and already evolved to the stage where runaway activity gets triggered in their nuclei (*2*).

Quasar activity is apparently a distinctive feature of *rather young* galaxies. The quasar density peaked soon after galaxies formed. The population then seems to have dwindled as the universe (with its constituent galaxies) got older. A current estimate (*3*) of the relative quasar density at different redshifts is shown on the left-hand side of Fig. 1. This same data can be presented much more dramatically in the manner shown on the right-hand side, where time and comoving density are plotted linearly rather than on logarithmic scales.

The integrated background light from quasars, estimated from quasar surveys, amounts to an energy density of around 3000 $M_\odot c^2$ per cubic megaparsec (*4*). This output is dominated by objects with redshift $z \simeq 2$, and of apparent magnitude 20 or 21. The present spatial density of galaxies is known, and we can therefore estimate the mean amount of energy per galaxy associated with quasar activity. If we take account only of the brighter galaxies (*5*), this amounts to around $10^6 h^{-3}$ solar rest masses per galaxy, h being Hubble's constant in units of 100 km s^{-1} Mpc^{-1}.

Many features of quasars remain enigmatic: active galactic nuclei display many phenomena on various scales and different wavebands, and it is hard to fit them into a single pattern. There is a strong consensus that the power output derives primarily from gravitation (rather than, for instance, nuclear energy) and that, to yield adequate efficiency, a relativistically deep potential well must be involved. The detailed modeling of the primary power output is complex, and in many respects still controversial [see, for example, (*6*) for a review]. But there is less room for doubt as to what a *dead*

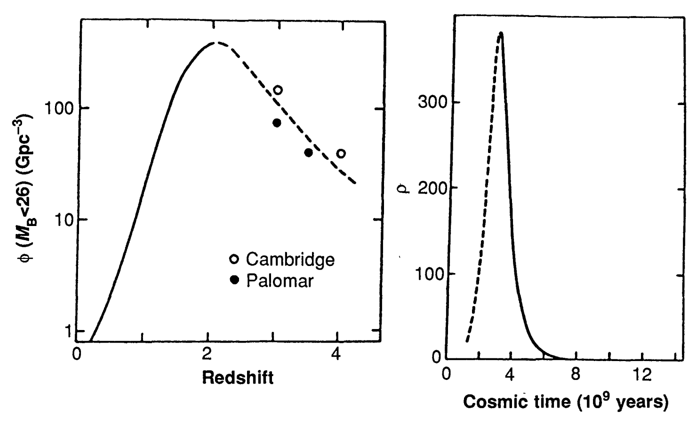

Fig. 1. The comoving density of powerful quasars is given on the left as a function of redshift z. (Beyond $z \simeq 3$ there is a falloff, but the quantitative details are uncertain. The filled and open circles correspond to the results from two different surveys.) The same comoving densities are, following Schmidt (*3*), replotted on the right on a linear scale; the horizontal axis in this plot is cosmic time, assuming an Einstein–de Sitter cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1}. This plot dramatizes the relative brevity of the "quasar era," when the universe was 2 to 3 billion years old.

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quasar should be: there seems no way of evading the conclusion that a substantial fraction of the mass involved must eventually collapse to a massive black hole. If we optimistically assign an efficiency of 10% to the overall energy generation in quasars, we must then conclude that their black hole remnants amount to an *average* of $10^7 h^{-3} M_\odot$ per bright galaxy (*4, 5*).

Even at the epoch of peak quasar activity, the comoving density of quasars was only 1 or 2% of the present galactic density. One might therefore surmise that quasar remnants would be expected in only 1 or 2% of galaxies, and that each would weigh around $10^{10} M_\odot$. However, we must remember that Fig. 1 delineates the evolution of the quasar *population*, which decays on a time scale of ~2 billion years. This may directly track the life cycle of a typical quasar; but there is the alternative possibility that individual quasars have much briefer lives, so that many generations flare and fade during the 2-billion-year period of peak quasar activity.

There have been many attempts to model the quasar luminosity function and its evolution. The lack of direct evidence on individual quasar lifetimes, or the "duty cycle" for the different kinds of activity in galactic nuclei, is a severe stumbling block. It seems very unlikely that the most luminous quasars could persist for a full 10^9 years—the resultant masses would then be $\gtrsim 10^{11} M_\odot$ unless their emission were narrowly beamed toward us. However, the situation is less clear for lower powered objects. We do not know whether individual quasars follow a standard evolutionary track, with bright and faint phases; the role of beaming is also still a controversial issue.

There are in principle other ways of estimating quasar masses. The optical spectrum of a quasar is dominated by emission lines from fast-moving clouds of gas, heated by continuum radiation from the central object. The distance of the clouds from the center can be estimated from the ionization state of the gas and their velocities from the line widths. If the cloud motions are gravitationally induced, one can therefore infer the central mass (*7*); if the gas is flowing out in a wind, we infer merely an upper limit. Some quasar models require a balance between radiation pressure and gravity: if electron scattering produces the main opacity, this requires a mass of $\sim 7 \times 10^7 [L/(10^{46} \text{ erg s}^{-1})] M_\odot$. If the power comes from accretion, radiation cannot overwhelm gravitation, so this mass sets (apart from beaming corrections) a *lower* limit (which is generally well below what is inferred from the emission lines).

Evidence on "dead quasar" masses could therefore offer clues to quasar structure, as well as to mean lifetimes, efficiencies, and so forth. And we must not forget that considerations relating to AGNs may greatly underestimate the mass and number of black holes in galaxies—the postulated 10% efficiency may be overoptimistic, and black holes could in principle also form via other routes than AGNs (or even be primeval).

Effects of Central Mass on Surrounding Stars

A massive black hole will inevitably influence the orbits of stars passing close to it, and evidence for just such effects in the centers of some nearby galaxies has recently been reported by several observers. To appreciate the nature of this evidence, it is helpful to define a few characteristic length scales. These are illustrated in Fig. 2 and its caption.

At the distances of even the nearest galaxies, the gravitational effect of the central black hole would be discernible only within an angular distance of a few arc seconds from the galactic nucleus (corresponding to r_h in Fig. 2). The first indications of such effects, dating from the late 1970s, related to the giant elliptical M87, where a mass of 3 to $5 \times 10^9 M_\odot$ was claimed on two separate grounds (*8*): a central peak in the light profile was attributed to the enhanced concentration of stars around a central dark mass; and the velocity dispersion appeared to rise from 300 km s^{-1} to >500 km s^{-1}, as would be expected if there were a central "$1/r$" potential. This discovery stimulated theoretical attempts to evade this conclusion, especially by invoking anisotropic velocity distributions [for example, (*9*)]. More recent observational work, particularly by Dressler (*10*) and Fillipenko (*11*), suggests that the situation is less straightforward. Much of the central peak in the light is now believed to be nonstellar in origin—this is not unexpected, since M87 is a radio source, whose well-known jet testifies to continuing nonthermal activity, at some level, in its nucleus. Furthermore, the rise in the stellar velocity dispersion is only confirmed up to a level of around 350 km s^{-1}. According to Dressler (*10*), the data do not require a black hole at all, but are compatible with a self-gravitating stellar distribution, whose mass-to-light ratio can be constant (rather than needing to rise towards the center) if the stellar orbits are predominantly radial. There *could*, nonetheless, be a hole of up to $10^9 M_\odot$ in M87: its gravitational effects would then show up only within $\lesssim 1$ arc second of the center.

M87 is a giant elliptical galaxy in the Virgo Cluster, ~20 Mpc away. At that distance, an angular scale of 1 arc second corresponds to 100-pc linear dimensions. There is obviously a better chance of detecting a $\lesssim 10^8 M_\odot$ hole within our nearest neighbor galaxies, more than ten times closer. Such evidence has now emerged, in a rather convincing form, especially within the Andromeda Galaxy (M31), our own galaxy's nearest major neighbor, only ~0.6 Mpc away.

In the 1960s, Schwarzschild and his Princeton colleagues built a small telescope, "Stratoscope," that could be flown in a high altitude balloon to avoid the blurring effect of the lower atmosphere. Its final flight, in 1971, revealed that the stars in the central few light-years of M31's core had a flattened distribution (*12*). In the last few years, Kormendy (*13*) and Dressler and Richstone (*14*) have taken spectra to study the motions of these stars. They find that the velocities rise

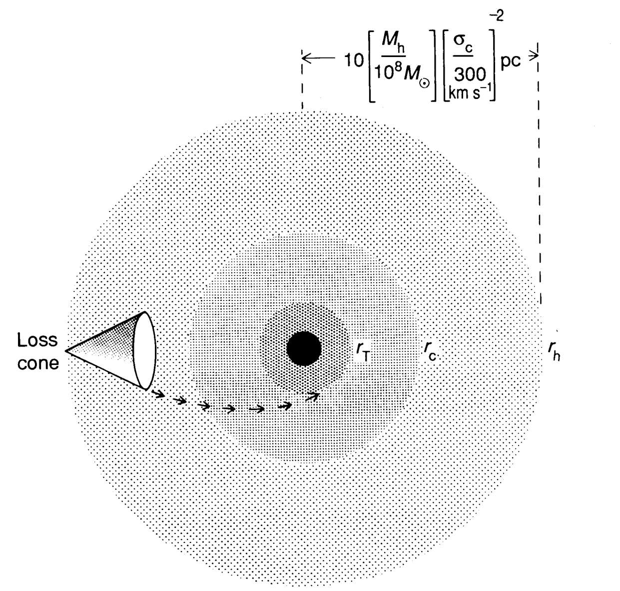

Fig. 2. This diagram depicts, not to scale, various characteristic radii around a massive black hole of mass M_h in a stellar system. If the velocity dispersion in the core of the galaxy is σ_c the hole influences the stellar motions within a radius $r_h \simeq (GM_h)/\sigma_c^2$. Within r_c stars would be moving so fast that they would be more likely to experience (generally disruptive) physical collisions with each other than to undergo two-body encounters of the kind that can be treated by point-mass approximations. r_c is the radius where the escape velocity from the hole is comparable with the escape velocity $v_* \simeq (2Gm_*/r_*)^{1/2}$ from the surface of a star. Tidal disruptions occur within a radius $r_T \simeq (M_h/m_*)^{1/3} r_*$. To be disrupted, a star must cross the sphere at $r \simeq r_h$ on a nearby radial "loss cone" orbit.

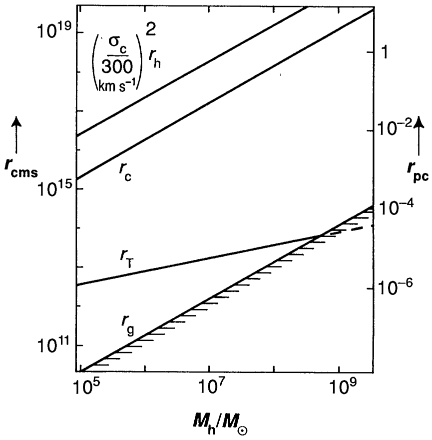

Fig. 3. The various radii depicted in Fig. 2 are plotted here, on a logarithmic scale, as a function of the hole mass M_h. The hole's gravitational radius is $r_g \simeq 1.5 \times 10^{13}$ $(M_h/10^8\ M_\odot)$ cm. The radii r_c and r_T are plotted for a solar-type star with $v_* \simeq 1000$ km s^{-1}. Note that a hole of $>>10^8\ M_\odot$ can swallow solar-type stars (though not, of course, giants) without first disrupting them. When $r_T \simeq r_g$, tidal disruption effects would be restricted to the general-relativistic domain where the hole's tidal effects cannot be adequately modeled by a r^{-3} Newtonian approximation.

towards the center, and that the flattened stellar system is rotating; moreover, the form of the rotation curve indicates that the gravitating mass, estimated to be in the range 3 to $7 \times 10^7\ M_\odot$, is more centrally concentrated than the stellar distribution itself. (see Fig. 4)

If the stars have an axisymmetric rotating distribution the mass-to-light ratio in the center exceeds 35 solar units. There are in principle alternative models which evade this conclusion: for instance, Gerhard (*15*) fits the data by a *non*-axisymmetric bar, with the major axis nearly along our line of sight. And there are still some puzzles in M31's nucleus—for instance, not only is the innermost region misaligned with the overall major axis (*13*), but the light distribution is not symmetrical around the apparent dynamical center (*16*). Nevertheless, the evidence for a central dark mass in M31 is much stronger than in the case of M87, in the sense that this conclusion can only be evaded by invoking rather contrived models.

Does a central body with high mass-to-light ratio, have to be a black hole? This is not self-evident. For instance, one might envisage a densely packed cluster of stars very different from those in the body of the galaxy—maybe neutron stars, or faint low-mass stars. The relaxation time t_{rel} for such a cluster, with mass M, composed of stars each of mass m_* (evaluated at the half-mass radius r) is approximately

$$t_{rel} \simeq 10^9 \left(\frac{m_*}{m_\odot}\right)^{-1} \left(\frac{M}{10^8 M_\odot}\right)^{1/2} (r/1\ \mathrm{pc})^{3/2}\ \mathrm{years} \quad (1)$$

so a cluster of 10^8 neutron stars, within a radius of 1 parsec, would have undergone core collapse within 10^{10} years. Moreover, a cluster containing a range of stellar masses evolves faster, because the heavier stars segregate towards the center (*17*). A cluster 10 light-years across (about 1 arc second at M31's distance), though an unappealing ad hoc choice, cannot be completely excluded. But it could be ruled out by the sharper images that the Hubble Space Telescope should soon provide: if the stars within the central 0.1 arc second were moving still faster, implying a still more compact concentration of dark matter than the present ~1 arc second resolution data require, this would rule out a cluster of many dark stars. A cluster so compact would evolve quickly, owing to stellar encounters, until some stars combined into a central hole and the others escaped; it would therefore be implausible to find it in a 10-billion-year-old galaxy.

The stars in the central bulge of the small nearby galaxy M32 are, as in M31, apparently rotating around a central mass (*18–20*), which in this case is $\sim 5 \times 10^6\ M_\odot$. There is also evidence for $10^9\ M_\odot$ in NGC 4594, the Sombrero galaxy (*21, 22*). In the latter case, however, there is less evidence for rotation and some of the same uncertainties pertain as for M87. Dressler and Richstone (*14*) conjecture that the masses may be proportional to the total mass in the bulge. Quasar remnants would then be found in ellipticals, the smaller holes in disc galaxies being relics of lower level activity such as is manifested by Seyfert galaxies.

Although one cannot yet exclude alternative interpretations of the apparent dark central mass concentration—which could conceivably involve a dense cluster, or be an artifact of anisotropic velocities for the visible stars—massive black holes certainly seem the most natural inference from this body of recent evidence. [For a recent assessment, see Goodman and Lee (*23*) or Binney and Petit (*24*).]

Flares from Tidally Disrupted Stars?

The presence of these holes is not surprising—indeed if we make the best guess about quasar lifetimes (and how many generations have lived and died) we would not be surprised, on the basis of the numbers, to find a black hole in most galaxies. Moreover, the data are consistent with the idea that galaxies accumulate central holes whose mass scales with the size of their stellar bulge (*14*). But before

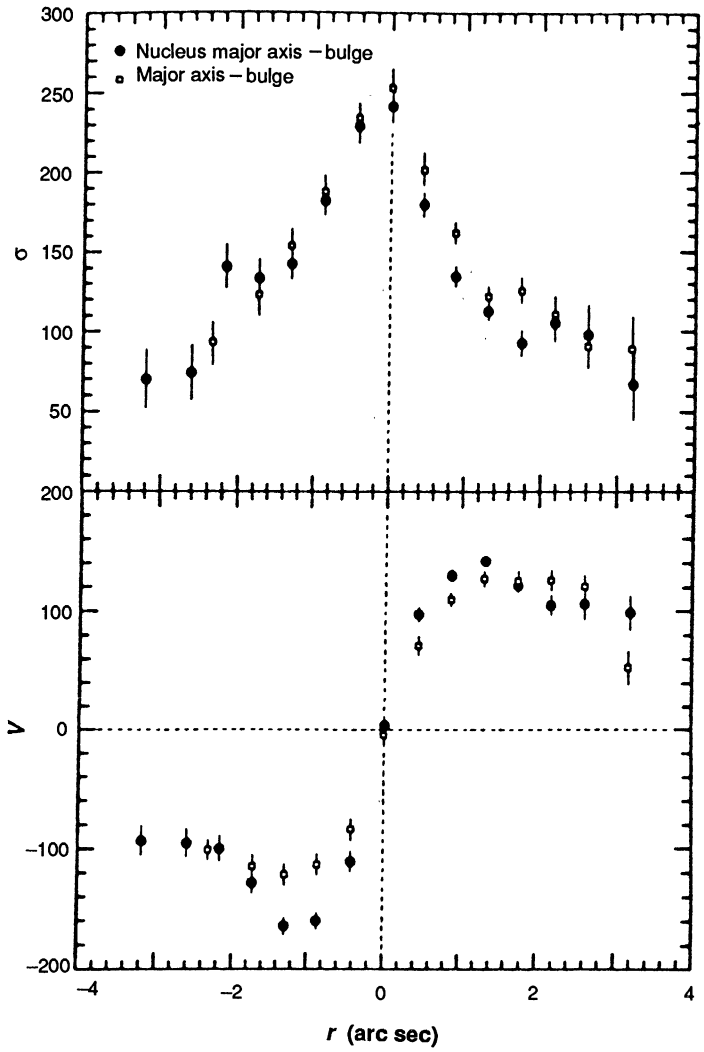

Fig. 4. Data from Kormendy (*13*) showing the velocity dispersion (upper panel) and rotation (lower panel) for stars in the nucleus of M31, the Andromeda Galaxy. Observations were made along the overall major axis, and also along the apparent major axis of the flattened nuclear star distribution whose orientation differs by 18°; the plotted velocities were obtained after subtracting the spectral contribution from the stars in the bulge.

accepting this conclusion (and dismissing alternative ideas involving, for instance, compact clusters of dark stars) we must ask a further question: can a black hole lurk in these quiescent galaxies without showing other evidence of its presence? We are used to the idea that black holes are implicated in the most powerful sources in the universe, and can (when accreting) be ultra-efficient radiators. But there is no sign of such activity in the Andromeda Galaxy (M31)—the upper limit is no more than a ten-thousandth of a quasar. So could a black hole be so completely starved of fuel that it does not reveal its presence as at least a "miniquasar"?

We do not directly know how much gas there is near the hole, and there is no a priori reason why this region should be "swept clean" of gas. The *star* density, however, is much better known—after all, if the stars were not closely packed near the center of the galaxy we would not have evidence for the black hole at all. Each star traces out a complicated orbit under the combined influence of all the other stars and of the hole itself. The orbits gradually change, or "diffuse," owing to the cumulative effect of encounters with other stars. There is a chance that these encounters will shift a star onto a nearly radial "loss cone" orbit (see Fig. 2) which brings it very close to the hole.

There is a limit to how closely a star can approach a black hole without suffering damage. One can calculate how close a passing star has to get for tidal forces to tear it apart. Any star passing within this "tidal radius" would be destroyed. The radius of a black hole scales with its mass, whereas the tidal radius goes only as the cube root. [The *volume* within the tidal radius is larger than that of the star by the same factor that the hole is more massive than the star.] The tidal forces at their "surfaces" are more gentle for holes of larger mass, and stars would be disrupted only after passing irreversibly inside an ultra-massive hole's horizon (see Fig. 3). A hole as large as the one claimed to exist in M87 could swallow a solar-type star without disrupting it. However, if the hole's mass is 5 to 100 million suns (the range relevant to the nearest galaxies) then, for stars like the sun, the tidal radius is 10 to 100 times larger than the hole itself.

It is an intricate (though tractable) problem in stellar dynamics to calculate the chance that a star passes within the central hole's tidal radius (*25–27*). If the hole's mass were $\sim 10^7 M_\odot$ such events would happen about once every few thousand years if the star density resembles that in the center of M31—the exact rate depends on the statistics of the stellar orbits, and particularly on how quickly the almost radial "loss cone" orbits are replenished. When a star is disrupted, there is bound to be some radiation from the sudden release of gas. The flares resulting from a disrupted star could be the clearest diagnostic of a black hole's presence.

When a rapidly changing tidal force starts to compete with a star's self-gravity, the material of the star responds in a complicated way, being stretched along the orbital direction, squeezed at right angles to the orbit, and strongly shocked. This phenomenon poses an as yet unmet challenge to computer simulations. Within a few years, detailed simulations should tell us what happens when stars of different types get tidally disrupted, and what radiation a distant observer might detect as the observational signature of such events. The relatively crude calculations so far carried out should, nevertheless, convey the essence of what goes on.

If the star density in the galactic nucleus, just outside r_h, is N_*, and the stellar velocities are $\sim \sigma_c$ (and isotropically distributed), then the rate of disruption is

$$\sim 10^{-3}\left(\frac{M_h}{10^7 M_\odot}\right)^{4/3}\left(\frac{N_*}{10^5 \text{ pc}^{-3}}\right)\left(\frac{\sigma_c}{300 \text{ km s}^{-1}}\right)^{-1} \text{year}^{-1} \quad (2)$$

The actual rate could be lower than this approximate expression because radial loss cone orbits get depleted. Or it could be higher, because stars accumulate on orbits between r_h and r_c, (see Fig. 2) and the density of stars in this cusp bound to the hole may exceed N_*. In fact, neither of these countervailing effects is likely to be of great importance for holes less massive than around $10^8 M_\odot$. Even the modest rate of stellar disruptions given above could have conspicuous consequences. If the debris from disrupted stars were all accreted by the hole, with efficiency 0.1 $\epsilon_{0.1}$, then the resultant mean luminosity would be

$$6 \times 10^{42}\left[\frac{\text{disruption rate}}{10^{-3} \text{ year}^{-1}}\right]\epsilon_{0.1} \text{ erg s}^{-1} \quad (3)$$

This predicted luminosity does not seem to be observed in M31. Do we therefore have to abandon the black hole interpretation of stellar motions in this and other galactic nuclei? The answer is "probably not," because of uncertainty about three things: (i) The fraction of the debris which is swallowed, rather than expelled; (ii) the radiative efficiency; and (iii) the time scale for accretion or expulsion of debris. Maybe we should expect bright flares with short duty cycles, rather than a steady luminosity?

The energy required to tear a star apart (that is, the star's self-binding energy) is of order $m_* v_*^2$, where $v_* \simeq (Gm_*/r_*)^{1/2}$. During tidal disruption, this energy is supplied at the expense of the orbital *kinetic* energy [which, at pericenter $\sim r_T$, is larger by $\sim (M_h/m_*)^{2/3}$]. Unless there were some explosive release of nuclear energy, which would be expected only if the star passes several times *closer* than r_T and were severely compressed by tidal forces (*28*), the debris would be *on average* bound to the hole (since typically $\sigma_c < v_*$).

Several effects would, however, impart orbital energies *spread widely about* this mean to gas from different parts of the disrupting star; this spread crucially influences what we would actually observe. The dominant such effect is the following. While falling inwards toward the hole, the star would develop a quadrupole distortion. The resultant gravitational torque would "spin it up" to a good fraction of its corotation angular velocity by the time it gets disrupted at $r \simeq r_T$: it would consequently, by that stage, be spinning at close to its breakup angular velocity. The parts on the "outside track" *furthest* from the hole would therefore have an *extra* velocity, over and above the orbital velocity $v_{orb} \simeq (2GM/r_T)^{1/2} \simeq c(r_g/r_T)^{1/2}$, of order $v_* = (m_*/M_h)^{1/3} v_{orb}$; those *closest* to the hole would have a comparable velocity *deficit*. There would consequently be a spread of order $v_{orb}\Delta v$, where $\Delta v \simeq v_*$, in the energies of different bits of debris (see Fig. 5 and its caption). Moreover, the slower moving gas on the "inside track" is deeper in the hole's potential well by $\sim (GM_h/r_T)(r_*/r_T) \simeq (Gm_*/r_*)(M_h/m_*)^{1/3}$, and this makes a comparable contribution to the energy spread of the debris. Other processes during the flyby—for instance, impulses from shocks or nuclear energy released during the drastic compression and distortion of the stellar material (*29–31*) could further enhance Δv.

Even though the *mean* specific binding energy of the debris to the hole would be positive, and comparable with the self-binding energy $(Gm_*/r_*) \simeq 10^{-5}c^2$ of the original star, the *spread about this mean* is larger by $(M_h/m_*)^{1/3}$—a factor which is $\gtrsim 100$ for hole masses in the range relevant to galactic nuclei (*32–34*). Whenever a solar-type star passes within the tidal disruption radius r_T of a hole with $M_h \gtrsim 10^6 M_\odot$, some of the debris would therefore be flung out on hyperbolic orbits with escape velocities up to 10^4 km s^{-1}; the *bound* debris would be on orbits with characteristic specific binding energy $\gtrsim 10^{-3}c^2$ rather than $\sim 10^{-5}c^2$. When solar-type stars are torn apart the orbital major axis of the most tightly bound debris is $\sim 10^3 M_6^{1/3} r_g$, where M_6 denotes the hole mass M_h in units of $10^6 M$; this material falls back after only $0.03 M_6^{1/2}$ years. For $M_6 \lesssim 100$ this is certainly small compared with the interval between successive disruptions (Eq. 2). Unless it takes many orbital periods to swallow the bound gas, the debris from each star would be digested separately—in contrast to Hills' (35) "debris cloud" model of quasars, where the disruptions were postulated to be frequent enough to generate (compare Eq. 3) a quasar-level luminosity, but the orbital periods of the debris ($\propto M_h^{1/2}$) are longer. The role of debris from disrupted stars in "activating" quiescent galaxies has been discussed by several authors, particularly by Ozernoi, Sanders, and their respective collaborators (36, 37), and preliminary numerical computations of stellar disruption have already been published (38, 39). The quantitative details of the smallest "flares" depend on viscosity, relativistic precession effects, and so on, and are explored more fully elsewhere (34, 40, 41).

When individual stars are being captured at the modest rate expected in relatively quiescent nuclei, the bulk of the debris from each would be swallowed or expelled *rapidly* compared with the interval between successive stellar captures. The most conspicuous result would be a flare (predominantly of thermal ultraviolet or x-ray emission) which may attain a quasar-level luminosity for a year or so before gradually fading (34, 40, 41).

The behavior of stars passing *well within* the tidal radius r_T exhibits special features. Such stars are not only elongated along the orbital direction but are even more severely compressed into a prolate shape (that is, a "pancake" aligned in the orbital plane) (28–31). This compression is halted by a shock, raising the matter (which then rebounds perpendicular to the orbital plane) to a higher adiabat. Also, there is the possibility of explosive nuclear energy release, and a still larger resultant spread in the energy of the debris. The orbits for which extreme compression occurs would enter regions where relativistic effects were more important than for those with $r_{min} = r_T$.

For hole masses $M_h \gtrsim 10^8 M_\odot$, solar-type stars cannot be disrupted without entering the strongly relativistic domain. The form of the black hole (Schwarzschild or Kerr?) then has an important quantitative effect, as does (for a rotating Kerr hole) the orientation of the stellar orbit relative to the hole's spin axis. Stars on counter-rotating orbits are more readily captured, with the result that Kerr holes would spin down if they gained mass primarily from stellar capture. When the hole mass is $>>10^8 M_\odot$ most main-sequence stars would be swallowed whole ($r_T \not> r_g$), and only giants would generate gaseous debris.

Observability of Flares from Disrupted Stars

The most distinctive consequence of a 10^6 to $10^8 M_\odot$ black hole's presence would be transient flares whenever bound debris from a star was swallowed, the luminosities being as high as $L_E \simeq 10^{44} M_6$ erg s^{-1}. In a given object, these flares would have a duty cycle of order 10^{-3} at peak luminosity. The rise time and the peak bolometric luminosity can be predicted with some confidence. However, the effective surface temperature (and thus also the fraction of the luminosity that emerges in the visible band) is harder to predict—this depends on the size of the effective photosphere that shrouds the hole, particularly when $\dot{M}$ is high. The median luminosity would be far below that which would result from *steady efficient* accretion of the mass supply implied by Eq. 2. Therefore we would not yet expect to have detected such a flare. On the other hand, a sufficiently large sample of such galaxies should reveal some members of the ensemble in a flaring state. Such events could be searched for out to large distances: they would last rather longer than supernovae and would differ from typical AGNs through the lack of any extended structure (emission line or radio components). The central location of the phenomenon, however, militates against its detection in supernova searches, which are notoriously incomplete in the inner high surface brightness regions of galaxies. If $\gtrsim 10^6 M_\odot$ holes were prevalent even in small galaxies, the nearest such flares, in any given year, may be no further away than the Virgo Cluster.

Several aspects of stellar disruption call for detailed stellar dynamical and hydrodynamic calculations, which cannot simulate the essence of the phenomenon without being fully three-dimensional. Also, relativistic precession has an important effect on the flow at $r \lesssim r_T$. Obviously, precise modeling should allow for a realistic range of stellar types and of impact parameters.

A further question is how fast the brightness fades after a flare. This is important because we want to know whether the center has faded below detectable levels before (1,000 to 10,000 years later) the next stellar disruption occurs. The answer to this question depends on how long it takes the last "dregs" of a disrupted star to be digested. Bits of debris that are on orbits bound to the hole, but only marginally so, will continue to rain down long after the bulk of the debris has been swallowed. One expects the infall rate $\dot{M}$ to decline at $t^{-5/3}$ for late times (34). Some material may, moreover, be stored for a long time in an accretion disc (40, 41): the specific angular momentum goes as $r^{1/2}$ for Keplerian orbits, so angular momentum transport via disc viscosity requires that 10% of the debris goes out to 100 r_T, and 1% to 10^4 r_T, before being swallowed. Even if the peak bolometric luminosity is sustained for $\lesssim 1$ year, a galactic nucleus may fade more slowly in the visible and infrared bands because of light echos and reprocessing of the ultraviolet flare by gas or dust within the central kiloparsecond.

If most galaxies harbor black holes, then if we look at the nearest few thousand galaxies we would expect to catch a few near the peak of a "flare," and probably rather more in a state where the effects of the most recent tidal disruption were still discernible. A highly worthwhile program would be to monitor all galaxies in the Virgo Cluster on an annual basis, seeking evidence for the occasional stellar disruption.

Mergers and Binary Black Holes

We have seen that there may be black holes in most galaxies. It is also implied by the data in Fig. 1 that most of these had already formed by the time the universe was 2 or 3 billion years old. There

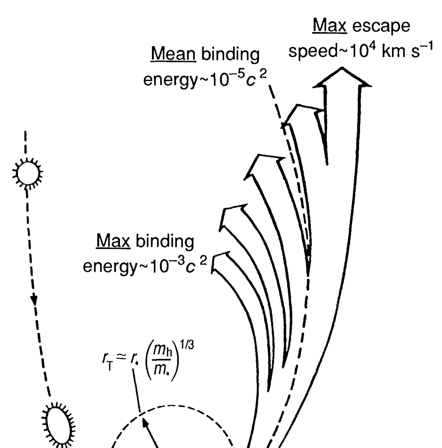

Fig. 5. A solar-type star approaching a massive black hole on a parabolic orbit with pericenter distance r_T is distorted and spun up during infall, and then tidally disrupted. The average specific binding energy of the debris to the hole is $\sim 10^{-5}$ c^2 (of order the self-binding energy of the original star). However, the *spread* in this energy [of order $v\Delta v$, where $v \sim c(r_T/r_g)^{-1/2}$ and $\Delta v \simeq (Gm_*/r_*)^{1/2}$] is $\gtrsim 10^{-3}$ c^2 for hole masses $M_h \gtrsim 10^6$ $M_\odot$. Almost half the debris would therefore escape on hyperbolic orbits with speeds up to $\sim 10^4$ km s^{-1}; the most tightly bound debris would traverse an elliptical orbit with major axis $\sim 10^3$ r_g before returning to $r \simeq r_T$. Radiation from this debris, much of which may swirl down into the hole, creates a conspicuous "flare."

have certainly been a substantial number of *galactic mergers* since that time. Indeed, according to the most popular "hierarchical" models for galaxy formation, the majority of large galaxies today will have experienced at least one merger. This raises the question of what happens during a merger if *each* of the galaxies involved harbors a central black hole.

Dynamical friction, operating on a time scale inversely proportional to the mass of the holes, quickly causes them to settle toward the center of the merged galaxy. The holes eventually approach close enough to become a binary, where each is influenced more by the gravitational pull of the other than by the galaxy's overall gravitational field. The black hole binary continues to tighten, as it transfers kinetic energy to passing stars, until it gets sufficiently close for gravitational radiation, operating on a time scale proportional to the fourth power of separation, to bring about eventual coalescence (*42*). The shape of the curve in Fig. 6 shows that a binary may spend a long time at a separation of order 10^4 or 10^5 r_g, with orbital velocity in the range 1000 to 3000 km s^{-1}. For its orbit to shrink by a factor of 2 through this range, the binary must interact with $\sim(M_h/m_*)$ stars, each of which is imparted a velocity of order the orbital speed, and therefore probably ejected from the galaxy. The time taken for the binary to shrink can be straightforwardly calculated if the stellar orbits are isotropic, but in practice the binary may expel the stars on nearly radial orbits in the galaxy faster than these can be replenished, in which case loss cone effects will reduce the rate of orbital shrinkage. Perhaps interaction with gas, which could be associated with an epoch of nuclear activity, is needed to bring the binary close enough for eventual coalescence (*43*).

If black holes in galaxies are brought together as a result of galactic mergers, the interesting question arises of whether the resultant holes remain in the merged galaxies. There may be a recoil due to emission of net *linear* momentum by gravitational waves in the final coalescence (*44*). If the holes have unequal masses, a preferred longitude in the orbital plane is determined by the orbital phase at which the final plunge occurs. For spinning holes there may be a rocket effect perpendicular to the orbital plane, since the spins break the mirror symmetry with respect to the orbital plane. The recoil is a strong field gravitational effect which depends essentially on there being a lack of symmetry in the system. It can therefore only be properly calculated when fully three-dimensional general relativistic calculations are feasible. The velocities arising from these processes, on the basis of very crude approximations, are likely to be several hundred kilometers per second. If a third hole drifts in before the binary has merged, a Newtonian "sling shot" may lead to ejection with speeds of order the orbital velocity of the binary, in other words up to 3000 km s^{-1} Some massive black holes could therefore be hurtling through intergalactic space, having broken loose from the galaxies in which they formed.

Our Own Galactic Center

There has for a number of years been dynamical evidence for a concentrated central mass of order 3×10^6 $M_\odot$ in our own galaxy. This evidence comes, however, primarily from the motions of gas streams rather than of stars. The gas could be subject to nongravitational forces, and therefore need not follow ballistic trajectories; there is therefore some ambiguity; but, in general, allowance for drag forces would *increase* the estimated central mass. In a recent review, Genzel and Townes (*45*) rated the net evidence as "substantial but not fully convincing."

A unique compact radio source appears to lie at the dynamical center of the galaxy (*46*). Its proper motion indicates that it is moving at <40 km s^{-1} relative to the center, and it can be naturally, though not uniquely, interpreted in terms of a model involving low-level accretion onto a black hole (*47*). There remains, however, a certain ambiguity because this source does not lie at the center of the pattern delineated by the peculiar arm-like gas features in the central 2 parsecs. Nor is it located symmetrically with respect to the several small objects (perhaps Wolf-Rayet stars) which make up the infrared source IRS 16.

The mean power input into the hot medium in which the gas streams are embedded is inferred to be higher than the present input. One can speculate that this, and the gas streams, could be the integrated effect of the last few tidally disrupted stars. Equation 2 suggests that one star may be swallowed every $\sim 10^4$ years. Unless there has been such an event especially recently (that is, within the last century or so) the current input would indeed be below its time-averaged level.

Two rather more speculative, but potentially more definitive, tests of whether there is indeed a massive black hole in our galactic center are worth a mention.

First, one can ask whether a single star could be tidally captured into a close circular orbit *without* disruption. Could it, for instance, have a series of pericenter passages with (say) $r \simeq 3r_T$, with tidal dissipation shrinking the orbit each time? Such a star would end up with an orbital period of order 1 hour, but a remarkable velocity exceeding $0.1c$. It is rather unlikely that a star could get into such an orbit without disruption, because in doing so it would have to radiate many times its own internal binding energy, on much less than its characteristic thermal time scale. However, a less extreme but related possibility, suggested by Hills (*48*), is that the stars in the central parseconds of our galaxy may include a population of close binaries. If such a binary got sufficiently near to the hole, it would be disrupted, one component being left in an eccentric bound orbit with period less than a year (which may then circularize), its companion being expelled at $\sim$1000 km s^{-1}. As we have seen, there seem to be massive black holes in most "normal" galaxies; such hypervelocity stars, if they were detectable, would be compelling testimony that our own galaxy is not underprivileged in this regard.

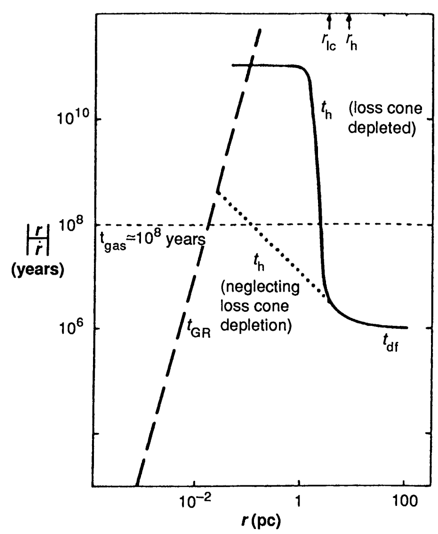

Fig. 6. The time scales involved in the approach, and eventual coalescence, of a supermassive binary [after Begelman, Blandford and Rees, (*42*)]. The core parameters chosen are those that might be appropriate to a giant elliptical: $\sigma_c \sim 300$ km s^{-1}, $N_* \sim 2 \times 10^3$ and $m_* \sim 1$. The members of the binary are taken to have masses $M_8 = 1$ and $m_8 = 0.3$. For this system the dynamical friction time is $t_{df} \sim 10^6$ years. Within r_h the evolution time scale would be $(r_h/r)t_{df}$ if loss cone depletion could be ignored; however, unless collective effects permit replenishment of the loss cone on much less than the ordinary stellar relaxation time, the evolution within r_{lc} proceeds on a very much longer time scale. Influx of gas into the system at a rate $\dot{M} \sim 1\ M_\odot$ per year would, however, yield a time scale $t_{gas} \simeq 10^8$ years. Gravitational radiation would take over as the dominant mechanism within 1.3×10^{-2} $(t_{gas}/10^8\ \text{years})^{1/4}$ pc, and the binary would then evolve towards coalescence. The recoil in the final burst may be enough to eject the newly merged hole from the core of the galaxy.

Conclusion

Discovery of black hole candidates in nearby galaxies will elucidate the "demography" of the quasar and AGN population (*4, 49*). It will also enable us to confront theoretical models of numerical simulations of tidal disruption, and so forth, with observations—and thereby, for the first time, test Einstein's theory in the strong field regime, to check whether space-time around such objects indeed obeys the metrics of Schwarzschild and of Kerr. There are, of course, *stellar*-mass black hole candidates in x-ray binaries within our own galaxy. But in the long run these hugely massive "dead quasars" in galactic nuclei (some as large as an entire solar system), whose formation and environment can be studied without the complexities of high density physics or high opacities, offer the firmest hope of exploring the most crucial and remarkable consequences of Einstein's theory.

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2. The redshift z is defined as $(\lambda_{\text{observed}} - \lambda_{\text{emitted}})/\lambda_{\text{emitted}}$. When the light set out from an object of redshift z, the "scale factor" of the universe would have been $(1 + z)^{-1}$ of its present value. If the cosmic expansion were undecelerated, the universe would then have been younger by this same factor. In the (theoretically popular) Einstein–de Sitter cosmology, the deceleration is such that the age of the universe actually scales as $(1 + z)^{-3/2}$. The current "record" redshift is $z = 4.73$ [D. Schneider, M. Schmidt, J. E. Gunn, *Astron. J.* **98**, 1951 (1989)]. The light from this object set out when, according to the Einstein–de Sitter model, the universe was $5.73^{-1.5} \simeq 0.07$ of its present age of $6.7 \times 10^9\ h^{-1}$ years, where $h = H_0/100$ km s^{-1} Mpc^{-1}. For a detailed discussion of high-z quasars and the problems involved in finding them, see P. Hewelt and S. Warren, *Rep. Prog. Phys.*, in press.
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