Supermassive Black Holes: Their Formation, and Their Prospects as Probes of Relativistic Gravity

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Abstract. The existence of supermassive collapsed objects in the cores of most galaxies poses still-unanswered questions. First, how did they form, and how does their mass depend on the properties of the host galaxy? Second, can observations probe the metric in the strong-field domain, testing whether it indeed agrees with the Kerr geometry predicted by general relativity (and, if so, what the spin is)?

1 Introduction

Compact dark objects, with deep gravitational potential wells, seem to lurk in most galactic centres; but current evidence cannot ‘diagnose’ the metric in the innermost region where Newtonian approximations break down. Several other speakers have described the status of the observations, as well as some aspects of theoretical models. This written text addresses two issues. How did supermassive holes form? And do they have Schwarzschild/Kerr metrics, thereby offering real prospects of testing our theories of strong-field gravity.

It has long been suspected that supermassive holes are implicated in the power output from active galactic nuclei (AGNs), and in the production of relativistic jets that energise strong radio sources. But the demography of these massive holes has been clarified by studies of relatively nearby galaxies: the centres of most of these display either no activity or a rather low level, but most seem to harbour dark central masses. Recent observational progress brings into sharper focus the question of how and when supermassive black holes formed, and how this process relates to galaxy formation.

There are now two spectacularly convincing cases of massive collapsed objects in nearby galaxies. The first, in the peculiar spiral NGC 4258, has been revealed by amazingly precise mapping of gas motions via the 1.3 cm maser-emission line of H₂O. [1,2]. The spectral resolution of this microwave line is high enough to pin down the velocities with accuracy of 1 km/sec. The Very Long Baseline Array achieves an angular resolution better than 0.5 milliarc seconds (100 times sharper than the HST, as well as far finer spectral resolution of velocities!). These observations have revealed, right in NGC 4258’s core, a disc with rotational speeds following an exact Keplerian law around a compact dark mass. The inner edge of the observed disc is orbiting
2 Martin J. Rees

at 1080 km/sec. It would be impossible to circumscribe, within its radius, a stable and long-lived star cluster with the inferred mass of $3.6 \times 10^7 \, M_{\odot}$.

The second utterly convincing candidate lies in our own Galactic Centre. Most nearby large galaxies seem to harbour massive central holes, so our own would seem underendowed if it did not have one too. Some have advanced this view for many years (eg ref [3]). Also, an unusual radio source has long been known to exist right at the dynamical centre of our Galaxy, which can be interpreted in terms of accretion onto a massive hole [4-6]. Direct evidence used to be ambiguous because intervening gas and dust in the plane of the Milky Way prevents us from getting a clear optical view of the central stars, as we can in, for instance, M 31. A great deal was known about gas motions, from radio and infrared measurements, but these were hard to interpret because gas does not move ballistically like stars, but can be influenced by pressure gradients, stellar winds, and other non-gravitational influences.

The situation was transformed by remarkable observations of stars in the near infrared band, where obscuration by intervening material is less of an obstacle. These are presented by Ekhart and by Ghez at this meeting. The speeds scale as $r^{-1/2}$ with distance from the centre, consistent with a hole of mass $2.5 \times 10^6 \, M_{\odot}$.

As other speakers will discuss, there is a crude proportionality between the hole’s mass and that of the central bulge or spheroid in the stellar distribution (which is of course the dominant part of an elliptical galaxy, but only a subsidiary component of a disc system like M31 or our own Galaxy). But how did the holes form?

2 AGN Demography and Black Hole Formation

Many of the faint smudges visible in the Hubble Deep Field [7] are galaxies with redshifts of order 3, being viewed at (or even before) the era when their spheroids formed. Physical conditions in the central potential wells of young and gas-rich galaxies should be propitious for black hole formation, and such processes are presumably connected with high-$z$ quasars. It now seems clear that most galaxies that existed at $z = 3$ would have participated subsequently in a series of mergers; giant present-day elliptical galaxies are the outcome of such mergers. Any black holes already present would tend to spiral inwards, and coalesce (unless a third body fell in before the merger was complete, in which case a Newtonian slingshot could eject all three: a binary in one direction; the third, via recoil, in the opposite direction).

The issues are then:
(a) how much does a black hole grow (and how much electromagnetic energy does it radiate) at each stage? and
(b) how far up the ‘merger tree’ did the first massive holes form? A single big galaxy can be traced back to the stage when it was in dozens of smaller components with individual internal velocity dispersions as low as 20 km/sec.
Did central black holes form even in these small and weakly bound systems? If so, they could have coalesced, in a hierarchical fashion, during subsequent mergers.

Perhaps black holes form with the same efficiency in small galaxies (with shallow potential wells), or maybe their formation had to await the buildup of substantial galaxies with deeper potential wells (i.e. with \( V \) above some threshold). This issue is important for the detectability of high-\( z \) miniquasars; it also determines whether the ionizing UV background at high redshifts has a nonthermal component that is able to ionize He as well as H.

The actual formation mechanism is still uncertain. More than 20 years ago, I presented a ‘flow diagram’ [8] which carried the message that it seemed likely – indeed almost inevitable - that large masses would collapse in galactic centres: there was indeed a variety of possible routes. We have now got used to the idea that black holes exist within most galaxies, but it is rather depressing that we still cannot decide which formation route is most likely.

One possibility is that the gas in a ‘proto-spheroid’ does not all break up into stellar-mass condensations, but that a supermassive star forms, which then collapses. As the gas evolved (through loss of energy and angular momentum) to higher densities and more violent internal dissipation, radiation pressure would prevent fragmentation, and puff it up into a single superstar [9,10]. Ordinary star formation may be suppressed even at less extreme densities – i.e. before the gas has become a single superstar – by other effects. For example, a magnetic field, even if not dynamically important overall, could inhibit fragmentation, especially because the free-electron concentration is unlikely to fall low enough to permit ambipolar diffusion, whereby the magnetic flux can escape from protostars in present-day molecular clouds.

Once a large mass of gas started to behave like a single superstar, it would continue to contract and deflate. Some mass would inevitably be shed, carrying away angular momentum, but the remainder would undergo complete gravitational collapse. This could be a substantial fraction – for example, if 10 percent of the mass had to be shed in order to allow contraction by a factor of 2, about 20 percent could form a black hole [10,11].

The mass of the hole would depend on that of its host galaxy, though not necessarily via an exact proportionality: the angular momentum of the protogalaxy and the depth of its central potential well are relevant factors too. Firmer and more quantitative conclusions will have to await elaborate numerical simulations. But it certainly seems in no way implausible that massive black holes form directly from gas (some, albeit, already processed through stars), perhaps after a transient phase as a supermassive object.

However, we cannot exclude the alternative ‘scenario’ where a massive star builds up within a dense central cluster of ordinary stars. The most detailed calculations were done by Quinlan and Shapiro ([12] and other references cited therein). These authors showed that stellar coalescence, followed by the segregation of the resultant high-mass stars towards the centre, could trigger
runaway evolution without (as earlier and cruder work had suggested) requiring implausible initial starting points. It would be well worthwhile extending these simulations to a wider range of initial conditions, and also to follow the build-up from stellar masses to supermassive object.

It is worth noting, incidentally, that whereas activity in low-$z$ galaxies may be correlated with some unusual disturbance due to a tidal encounter or merger, this may not be the right way to envisage the more common high-$z$ quasars, since almost all high-$z$ galaxies are ‘disturbed’, in the sense that they are nearly always experiencing a merger or disturbance that is sufficient to perturb axisymmetry or to trigger a large inflow of gas.

The most massive black holes would have gained mass through a succession of mergers, as well as through accretion of gas at each stage. Haehnelt and Kauffmann ([13], and these proceedings) have modelled this in the context of semi-analytic schemes for galaxy evolution, and have achieved a good fit with the luminosity function and $z$-dependence of quasars.

3 Do the Candidate Holes Obey the Kerr Metric?

3.1 Probing near the hole

The observed molecular disc in NGC 4258 lies a long way out: at around $10^5$ gravitational radii. We can exclude all conventional alternatives (dense star clusters, etc); however, the measurements tell us nothing about the central region where gravity is strong – certainly not whether the putative hole actually has properties consistent with the Kerr metric. The stars closest to our Galactic Centre likewise lie so far out from the putative hole (their speeds are less than 1 percent that of light) that their orbits are essentially Newtonian.

We can infer from AGNs that ‘gravitational pits’ exist, which must be deep enough to allow several percent of the rest mass of infalling material to be radiated from a region compact enough to vary on timescales as short as an hour. But we still lack quantitative probes of the relativistic region. We believe in general relativity primarily because it has been resoundingly vindicated in the weak field limit (by high-precision observations in the Solar System, and of the binary pulsar) – not because we have evidence for black holes with the precise Kerr metric.

Relativists would seize eagerly on any relatively ‘clean’ probe of the strong-field domain. The emission from most accretion flows is concentrated towards the centre, where the potential well is deepest and the motions fastest. Such basic features of the phenomenon as the overall efficiency, the minimum variability timescale, and the possible extraction of energy from the hole itself all depend on inherently relativistic features of the metric – on whether the hole is spinning or not, how it is aligned, etc. But the data here are imprecise and ‘messy’. We would occasionally expect to observe, even in quiescent nuclei, the tidal disruption of a star. Exactly how this happens would depend on distinctive precession effects around a Kerr metric, but the
gas dynamics are so complex that even when a flare is detected it will not serve as a useful diagnostic of the metric in the strong-field domain. There are however several encouraging new possibilities.

3.2 X-ray spectroscopy of accretion flows

Optical spectroscopy tells us a great deal about the gas in AGNs. However, the optical spectrum originates quite far from the hole. This is because the innermost regions would be so hot that their thermal emission emerges as more energetic quanta. X-rays are a far more direct probe of the relativistic region. The appearance of the inner disc around a hole, taking doppler and gravitational shifts into account, along with light bending, was first calculated by Bardeen and Cunningham [14] and subsequently by several others (eg [15]). There is of course no hope (until X-ray interferometry is developed) of actually ‘imaging’ these inner discs. However, the large frequency-shifts could reveal themselves spectroscopically — substantial gravitational red-shifts would be expected, as well as large doppler shifts [15]. Until recently, the energy resolution and sensitivity of X-ray detectors was inadequate to permit spectroscopy of extragalactic objects. The ASCA X-ray satellite was the first with the capability to measure emission line profiles in AGNs. There is already one convincing case [16] of a broad asymmetric emission line — indicative of a relativistic disc, and others should soon follow. The value of \((a/m)\) can in principle be constrained too, because the emission is concentrated closer in, and so displays larger shifts, if the hole is rapidly rotating, and there is some evidence that this must be the case in MCG -6-30-15 [17].

The Chandra and XMM X-ray satellites should be able to extend and refine these studies; they may offer enough sensitivity, in combination with time-resolution, to study flares, and even to follow a ‘hot spot’ on a plunging orbit.

The swing in the polarization vector of photon trajectories near a hole was long ago suggested [18] as another diagnostic; but this is still not feasible because X-ray polarimeters are far from capable of detecting the few percent polarization expected.

3.3 The Blandford-Znajek process

Blandford and Znajek [19] showed that a magnetic field threading a hole (maintained by external currents in, for instance, a torus) could extract spin energy, converting it into directed Poynting flux and electron-positron pairs. Can we point to objects where this is definitively happening? The giant radio lobes from radio galaxies sometimes spread across millions of lightyears – \(10^{10}\) times larger than the hole itself. If the Blandford-Znajek process is really going on, these huge structures may be the most direct manifestation of an inherently relativistic effect around a Kerr hole.
Jets in some AGNs definitely have Lorentz factors exceeding 10. Moreover, some are probably Poynting-dominated, and contain pair (rather than electron-ion) plasma. But there is still no compelling reason to believe that these jets are energised by the hole itself, rather than by winds and magnetic flux ‘spun off’ the surrounding torus. The case for the Blandford-Znajek mechanism would be strengthened if baryon-free jets were found with still higher Lorentz factors, or if the spin of the holes could be independently measured, and the properties of jets turned out to depend on \( a/m \).

The process cannot dominate unless either the field threading the hole is comparable with that in the orbiting material, or else the surrounding material radiates with low radiative efficiency. These requirements cannot be ruled out, though there has been recent controversy about how plausible they are. (It may be worth noting that the Blandford-Znajek effect could also be important in the still more extreme context of gamma-ray bursts, where a newly formed hole of a few solar masses could be threaded by a field exceeding \( 10^{15} \text{ G} \).)

### 3.4 What is the expected spin?

The spin of a hole affects the efficiency of ‘classical’ accretion processes; the value of \( a/m \) also determines how much energy is in principle extractable by the Blandford-Znajek effect. Moreover, the orientation of the spin axis may be important in relation to jet production, etc.

Spin-up is a natural consequence of prolonged disc-mode accretion: any hole that has (for instance) doubled its mass by capturing material that is all spinning the same way would end up with \( a/m \) being at least 0.5. A hole that is the outcome of a merger between two of comparable mass would also, generically, have a substantial spin. On the other hand, if it had gained its mass from capturing many low-mass objects (holes, or even stars) in randomly-oriented orbits, \( a/m \) would be small.

### 3.5 Precession and alignment

Most of the literature on gas dynamics around Kerr holes assumes that the flow is axisymmetric. This assumption is motivated not just by simplicity, but by the expectation that Lense-Thirring precession would impose axisymmetry close in, even if the flow further out were oblique and/or on eccentric orbits. Plausible-seeming arguments, dating back to the pioneering 1975 paper by Bardeen and Petterson [20], suggested that the alignment would occur, and would extend out to a larger radius if the viscosity were low because there would be more time for Lense-Thirring precession to act on inward-spiralling gas. However, later studies, especially by Pringle, Ogilvie, and their associates, have shown that naive intuitions can go badly awry. The behaviour of the ‘tilt’ is much more subtle; the effective viscosity perpendicular to the disc plane can be much larger than in the plane. In a thin disc, the alignment
effect is actually weaker when viscosity is low. What happens in a thick torus is still unclear, and will have to await 3-D gas-dynamical simulations. The orientation of a hole’s spin and the innermost flow patterns could have implications for jet alignment. An important paper by Pringle and Natarajan [21] shows that ‘forced precession’ effects due to torques on a disc can lead to swings in the rotation axis that are surprisingly fast (i.e. on timescales very much shorter than the timescale for changes in the hole’s mass).

3.6 Stars in relativistic orbits?

Gas-dynamical phenomena are complicated because of viscosity, magnetic fields etc. It would be nice to have a ‘cleaner’ and more quantitative probe of the strong-field regime: for instance, a small star orbiting close to a supermassive hole. Such a star would behave like a test particle, and its precession would probe the metric in the ‘strong field’ domain. These interesting relativistic effects, have been computed in detail by Karas and Vokrouhlicky [22, 23]. Would we expect to find a star in such an orbit? An ordinary star certainly cannot get there by the kind of ‘tidal capture’ process that can create close binary star systems. This is because the binding energy of the final orbit (a circular orbit with the same angular momentum as an initially near-parabolic orbit with pericentre at the tidal-disruption radius) would have to be dissipated within the star, and that cannot happen without destroying it. Syer, Clarke and Rees [24] pointed out, however, that an orbit can be ‘ground down’ by successive impacts on a disc (or any other resisting medium) without being destroyed: the orbital energy then goes almost entirely into the material knocked out of the disc, rather than into the star itself. Other constraints on the survival of stars in the hostile environment around massive black holes – tidal dissipation when the orbit is eccentric, irradiation by ambient radiation, etc – are explored by Podsiadlowski and Rees [25], and King and Done [26]. They can be thought of as close binary star systems with extreme mass ratios.

These stars would not be directly observable, except maybe in our own Galactic Centre. But they might have indirect effects: such a rapidly-orbiting star in an active galactic nucleus could signal its presence by quasiperiodically modulating the AGN emission.

3.7 Gravitational-wave capture of compact stars

Neutron stars or white dwarfs circling close to supermassive black holes would be impervious to tidal dissipation, and would have such a small geometrical cross section that the ‘grinding down’ process would be ineffective too. On the other hand, because they are small they can get into very tight orbits by straightforward stellar-dynamical processes. For ordinary stars, the ‘point mass’ approximation breaks down for encounter speeds above 1000 km/s – physical collisions are then more probable than large-angle deflections. But
there is no reason why a ‘cusp’ of tightly bound compact stars should not extend much closer to the hole. Neutron stars or white dwarfs could exchange orbital energy by close encounters with each other until some got close enough that they either fell directly into the hole, or until gravitational radiation became the dominant energy loss. When stars get very close in, gravitational radiation losses become significant, and tend to circularise an elliptical orbit with small pericentre. Most such stars would be swallowed by the hole before circularisation, because the angular momentum of a highly eccentric orbit ‘diffuses’ faster than the energy does due to encounters with other stars, but some would get into close circular orbits [27,28].

A compact star is less likely than an ordinary star in similar orbit to ‘modulate’ the observed radiation in a detectable way. But the gravitational radiation (almost periodic because the dissipation timescale involves a factor \(M_{\text{hole}}/m^*\)) would be detectable.

3.8 Scaling laws and ‘microquasars’

Two galactic X-ray sources that are believed to involve black holes generate double radio structures that resemble miniature versions of the classical extragalactic strong radio sources. These are discussed in the paper by Mirabel. The jets have been found to display apparent superluminal motions across the sky, indicating that, like the extragalactic radio sources, they contain plasma that is moving relativistically.

There is no reason to be surprised by this analogy between phenomena on very different scales. Indeed, the physics is exactly the same, apart from very simple scaling laws. If we define \(l = L/L_{\text{Ed}}\) and \(\dot{m} = \dot{M}/M_{\text{crit}}\), where \(M_{\text{crit}} = L_{\text{Ed}}/c^2\), then for a given value of \(\dot{m}\), the flow pattern may be essentially independent of \(M\). Linear scales and timescales, of course, are proportional to \(M\), and densities in the flow scale as \(M^{-1}\). The physics that amplifies and tangles any magnetic field may be scale-independent, and the field strength B scales as \(M^{-1/2}\). So the bremsstrahlung or synchrotron cooling timescales go as \(M\), implying that \(t_{\text{cool}}/t_{\text{dyn}}\) is insensitive to \(M\) for a given \(\dot{m}\). So also are ratios involving, for instance, coupling of electron and ions in thermal plasma. Therefore, the efficiencies and the value of \(l\) are insensitive to \(M\), and depend only on \(\dot{m}\). Moreover, the form of the spectrum, for given \(\dot{m}\), depends on \(M\) only rather insensitively (and in a manner that is easily calculated).

The kinds of accretion flow inferred in, for instance, M87, giving rise to a compact radio and X-ray source, along with a relativistic jet, could operate just as well if the hole mass was lower by a hundred million, as in the galactic LMXB sources. So we can actually study the same processes involved in AGNs in microquasars close at hand within our own galaxy. And these miniature sources may allow us to observe a simulacrum of the entire evolution of a strong extragalactic radio source, its life-cycle speeded up by a similar factor.
3.9 Discoseismology

Disks or tori that are maintained by steady flow into a black hole can support vibrational modes [29-31]. The frequencies of these modes can, as in stars, serve as a probe for the structure of the inner disc or torus. The amplitude depends on the importance of pressure, and hence on disc thickness; how they are excited, and the amplitude they may reach, depends, as in the Sun, on interaction with convective cells and other macroscopic motions superimposed on the mean flow. But the frequencies of the modes can be calculated more reliably. In particular, the lowest g-mode frequency is close to the maximum value of the radial epicyclic frequency $k$. This epicyclic frequency is, in the Newtonian domain, equal to the orbital frequency. It drops to zero at the innermost stable orbit. It has a maximum at about $9GM/c^2$ for a Schwarzschild hole; for a Kerr hole, $k$ peaks at a smaller radius (and a higher frequency for a given $M$). The frequency is 3.5 times higher for $(a/m) = 1$ than for the Schwarzschild case.

Novak and Wagoner [31] pointed out that these modes may cause an observable modulation in the X-ray emission from galactic black hole candidates. Just such effects have been seen in GRS 1915+105 [32]. The amplitude is a few percent (somewhat larger at harder X-ray energies) suggesting that the oscillations involve primarily the hotter inner part of the disc. The fluctuation spectrum shows a peak in Fourier space at around 67 Hz. This frequency does not change even when the X-ray luminosity doubles, suggesting that it relates to a particular radius in the disc. If this is indeed the lowest g-mode, and if the simple disc models are relevant, then the implied mass is $10.2 M_\odot$ for Schwarzschild, and $35 M_\odot$ for a ‘maximal Kerr’ hole (Nowak et al 1997). The mass of this system is not well known. However, this technique offers the exciting prospect of inferring $(a/m)$ for holes whose masses are independently known.

GRS 1915+105 is one of the objects with superluminal radio jets. The simple scaling arguments section 3.8. imply that the AGNs which it resembles might equally well display oscillations with the same cause. However, the periods there would be measured in days, rather than fractions of a second.

4 Gravitational Radiation as a Probe

4.1 Gravitational waves from newly-forming massive holes?

The gravitational radiation from black holes offers impressive tests of general relativity, involving no physics other than that of spacetime itself.

At first sight, the formation of a massive hole from a monolithic collapse might seem an obvious source of strong wave pulses. The wave emission would be maximally intense and efficient if the holes formed on a timescale as short as $r_g/c$, where $r_g = (GM/c^2)$ — something that might happen if they built up via coalescence of smaller holes (cf ref [12]).
If, on the other hand, supermassive black holes formed as suggested in section 2 – directly from gas (some, albeit, already processed through stars), perhaps after a transient phase as a supermassive object – then the process may be too gradual to yield efficient gravitational radiation. That is because post-Newtonian instability is triggered at a radius $r_i > r_g$. Supermassive stars are fragile because of the dominance of radiation pressure: this renders the adiabatic index only slightly above $4/3$ (by an amount of order $10(M/M_\odot)^{-1/2}$). Since $\gamma = 4/3$ yields neutral stability in Newtonian theory, even the small post-Newtonian corrections then destabilize such ‘superstars’. The characteristic collapse timescale when instability ensues is longer than $r_g/c$ by the $3/2$ power of the collapse factor.

The post-Newtonian instability is suppressed by rotation. A differentially rotating supermassive star could in principle support itself against post-Newtonian instability until it became very tightly bound. It could then perhaps develop a a bar-mode instability and collapse within a few dynamical times. To achieve this tightly-bound state without drastic mass loss, the object would need to have deflated over a long timescale, losing energy at no more than the Eddington rate.

The formation of a hole ‘in one go’ from a supermassive star is an unpromising source of gravitational waves. On the other hand, strong signals are expected when already-formed holes coalesce, as the aftermath of mergers of their host galaxies.

The gravitational waves associated with supermassive holes would be concentrated in a frequency range around a millihertz – too low to be accessible to ground-based detectors, which lose sensitivity below 100 Hz, owing to seismic and other background noise. Space-based detectors are needed. One such, proposed by the European Space Agency, is the Laser Interferometric Spacecraft (LISA) – three spacecraft on solar orbit, configured as a triangle, with sides of 5 million km long whose length is monitored by laser interferometry.

4.2 Gravitational waves from coalescing supermassive holes.

The guaranteed sources of really intense gravitational waves in LISA’s frequency range would be coalescing supermassive black holes. Many galaxies have experienced a merger since the epoch $z > 2$ when, according to ‘quasar demography’ arguments they acquired central holes. The holes in the two merging galaxies would spiral together, emitting, in their final coalescence, up to $\sim 10$ per cent of their rest mass as a burst of gravitational radiation in a timescale of only a few times $r_g/c$. These pulses would be so strong that LISA could detect them with high signal-to-noise even from large redshifts. Whether such events happen often enough to be interesting can to some extent be inferred from observations (we see many galaxies in the process of coalescing), and from simulations of the hierarchical clustering process whereby galaxies and other cosmic structures form. Haehnelt [33 and later
references] has calculated the merger rate of the large galaxies believed to harbour supermassive holes: it is only about one event per century, even out to redshifts $z = 4$. However, big galaxies are probably the outcome of many successive mergers. As discussed in Section 2, we still have no direct evidence — nor firm theoretical clues — on whether these small galaxies harbour black holes (nor, if they do, of what the hole masses typically are). However it is certainly possible that enough holes of (say) $10^5 M_\odot$ lurk in small early-forming galaxies to yield, via subsequent mergers, more than one event per year detectable by LISA.

LISA is potentially so sensitive that it could detect the nearly-periodic waves from stellar-mass objects orbiting a $10^5 - 10^6 M_\odot$ hole, even at a range of a hundred Mpc, despite the $m^*/M_{\text{hole}}$ factor whereby the amplitude is reduced compared with the coalescence of two objects of comparable mass $M_{\text{hole}}$. The stars in the observed ‘cusps’ around massive central holes in nearby galaxies are of course (unless almost exactly radial) on orbits that are far too large to display relativistic effects. Occasional captures into relativistic orbits can come about by dissipative processes — for instance, interaction with a massive disc [24,34]. But unless the hole mass were above $10^8 M_\odot$ (in which case the waves would be at too low a frequency for LISA to detect), solar-type stars would be tidally disrupted before getting into relativistic orbits. Interest therefore focuses on compact stars, for which dissipation due to tidal effects or drag is less effective. As described in Section 3.7, compact stars may get captured as a result of gravitational radiation, which can gradually ‘grind down’ an eccentric orbit with close pericenter passage into a nearly-circular relativistic orbit. The long quasi-periodic wave trains from such objects, modulated by orbital precession (cf refs [22,23]) in principle carries detailed information about the metric.

The attraction of LISA as an ‘observatory’ is that even conservative assumptions lead to the prediction that a variety of phenomena will be detected. If there were many massive holes not associated with galactic centres (not to mention other speculative options such as cosmic strings), the event rate would be much enhanced. Even without factoring on an ‘optimism factor’ we can be confident that LISA will harvest a rich stream of data.

LISA is now being actively studied both in Europe and the US. If funded jointly by ESA and NASA, it could fly within ten years.

### 4.3 Gravitational-wave recoil

Is there any way of learning, before that date, something about gravitational radiation? The dynamics (and gravitational radiation) when two holes merge has so far been computed only for cases of special symmetry. The more general problem — coalescence of two Kerr holes with general orientations of their spin axes relative to the orbital angular momentum — is a ‘grand challenge’ computational project being tackled at the MPI in Potsdam, and at US centres. When this challenge has been met (and it will almost certainly not...
take all the time until LISA flies) we shall find out not only the characteristic wave form of the radiation, but the recoil that arises because there is a net emission of linear momentum.

There would be a recoil due to the non-zero net linear momentum carried away by gravitational waves in the coalescence. 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, additionally, be a rocket effect perpendicular to the orbital plane, since the spins break the mirror symmetry with respect to the orbital plane. [35]

The recoil is a strong-field gravitational effect which depends essentially on the lack of symmetry in the system. It can therefore only be properly calculated when fully 3-dimensional general relativistic calculations are feasible. The velocities arising from these processes would be astrophysically interesting if they were enough to dislodge the resultant hole from the centre of the merged galaxy, or even eject it into intergalactic space. This recoil could displace the hole from the centre of the merged galaxy – it might therefore be relevant to the low–$z$ quasars that seem to be asymmetrically located in their hosts (and which may have been activated by a recent merger). Even galaxies that do not harbour a central hole may, therefore, once have done so in the past. The core of a galaxy that has experienced such an ejection event may retain some trace of it (perhaps, for instance, an unusual profile), because the energy transferred to stars via dynamical friction during the merger process (cf [36]).

The recoil might even be so violent that the merged hole breaks loose from its galaxy and goes hurtling through intergalactic space. This disconcerting thought should at least impress us with the reality and ‘concreteness’ of the extraordinary entities to whose discovery Riccardo Giacconi contributed so much.

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