Bull. Astr. Soc. India (2003) **31**, 121–139

# The Realm of the Supermassive Black Holes

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One of the paradigms of astronomy at the dawn of the new millennium is that most galaxies, if not all, have massive black holes at their centres. In this talk, I wish to highlight the arguments that led one to this conclusion, the current observational evidence in support of this paradigm and also the possible formation mechanisms of such supermassive black holes.

Soon after Quasars were discovered in the 1960s, observations suggested that their central energy source must be supermassive black holes. The basic argument was the following.

1. Quasars are incredibly luminous objects.

$$L \sim 10^{46}\text{erg/s} \sim 10^{12}L_\odot \qquad (1)$$

   This implied that the mass of the quasar must be greater than $10^8 M_\odot$. This follows from concept of the Eddington Luminosity Limit of $10^{38}$erg/s for a solar mass object. This limiting luminosity obtains when the gravitational pressure is precisely balanced by the outward radiation pressure. In a steady state, the luminosity of a self gravitating object cannot exceed this. This powerful argument implies that a luminosity of $10^{46}$erg/s can only be produced by an object of mass greater than $10^8 M_\odot$.

2. Extraordinarily, the flux from quasars varies with time! If the luminosity of an object varies in a timescale $\sim \Delta t$, then the size of the object must be less than (velocity of light $\times$ $\Delta$t). The variability of quasars suggested that they must be very compact objects. Some quasars change their luminosity in a few minutes which implies that their size must be much less than that of the solar system!

3. Such a large mass ($> 10^8 M_\odot$) of such a small size ($< 10^{13}$cm) implied a black hole.

The small size, together with the enormous energy output led several people, including Zeldovich (1964), Salpeter (1964) and Lynden-Bell (1978), to argue that an accreting central massive black hole must be the central engine. The key argument was that the ratio of gravitational energy

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released to the nuclear energy released must be large. Recent observations of micro-arcsecond jets and rapid x-ray variability have constrained the compactness and efficiency even more strongly. The argument that the energy released must be the gravitational binding energy as matter falls into a deep potential well is compelling. *A central black hole accreting from a disk is the most conservative hypothesis.*

**Dynamical Evidence**: The first dynamical evidence for a Supermassive Black Hole - although not iron clad - came from the observation of the giant elliptical galaxy $M87$. The study of stellar kinematics showed that the velocity dispersion rose to $\sim$ 400 km/s towards the centre, implying a centrally condensed mass of $5 \times 10^9 M_\odot$ (Sargent 1978). More convincing evidence came recently from the Hubble Space Telescope observations which revealed a small gas disk at the centre of the galaxy (Harms et al. 1994; Ford et. al. 1994) The velocity of the gas about the centre yielded a mass of $3.7 \times 10^9 M_\odot$ for the central object. But this still wasn't convincing evidence that the central object was a *black hole.*

However, this has recently been established beyond reasonable doubt in two cases.

**NGC 4258**: The first case is the galaxy NGC 4258. In 1995, Miyoshi and his collaborators made a remarkable observation using the maser emission from water molecules, and using high angular resolution technique (Miyoshi et al. 1995). The spectral resolution of this observation at 22 GHz was so high that they could determine velocities to an accuracy of 1 km/s! They used very long baseline interferometry to achieve an angular resolution of 0.5 milli arc seconds, a hundred times better than the resolution of HST! This remarkable observation reveals the following. The galaxy contains a distribution of maser spots as shown in the upper panel of Figure 1. They are distributed in an almost-linear structure passing through the projected centre of the galaxy, with features on one side **redshifted** relative to the galaxy's systemic velocity, while those on the other side are **blueshifted**. The natural explanation is that the maser spots lie in an edge-on disk orbiting a large central mass.

Confirmation of this model has come from the Doppler shifts of the **individual** spots. As seen clearly in the figure, the line-of-sight velocity drops off as $r^{-\frac{1}{2}}$, exactly as would be expected from Kepler's laws. At small projected radii, the line of sight velocity increases *linearly* with distance. This can only occur *if these masers lie on a single circular orbit!* The picture one arrives at is the following. There is an accretion disk around a central mass. This disk is filled with maser spots. The inner edge of the accretion disk is defined by a ring of masers. The inner edge of the disk is at 0.13 parsec, and the outer edge at 0.26 parsec. The inner edge is rotating at 1080 km/s.

The derived mass of the central object is $3 \times 10^7 M_\odot$, equivalent to an incredibly high mass density of $> 10^9 M_\odot / pc^3$. The important point is that it would be virtually impossible to circumscribe within the annular disk a stable and long-lived star cluster of mass $3.6 \times 10^7 M_\odot$ (a detailed argument for this is given later). *Thus, in the case of NGC 4258 one can assert with considerable confidence that the central object has to be a black hole.*

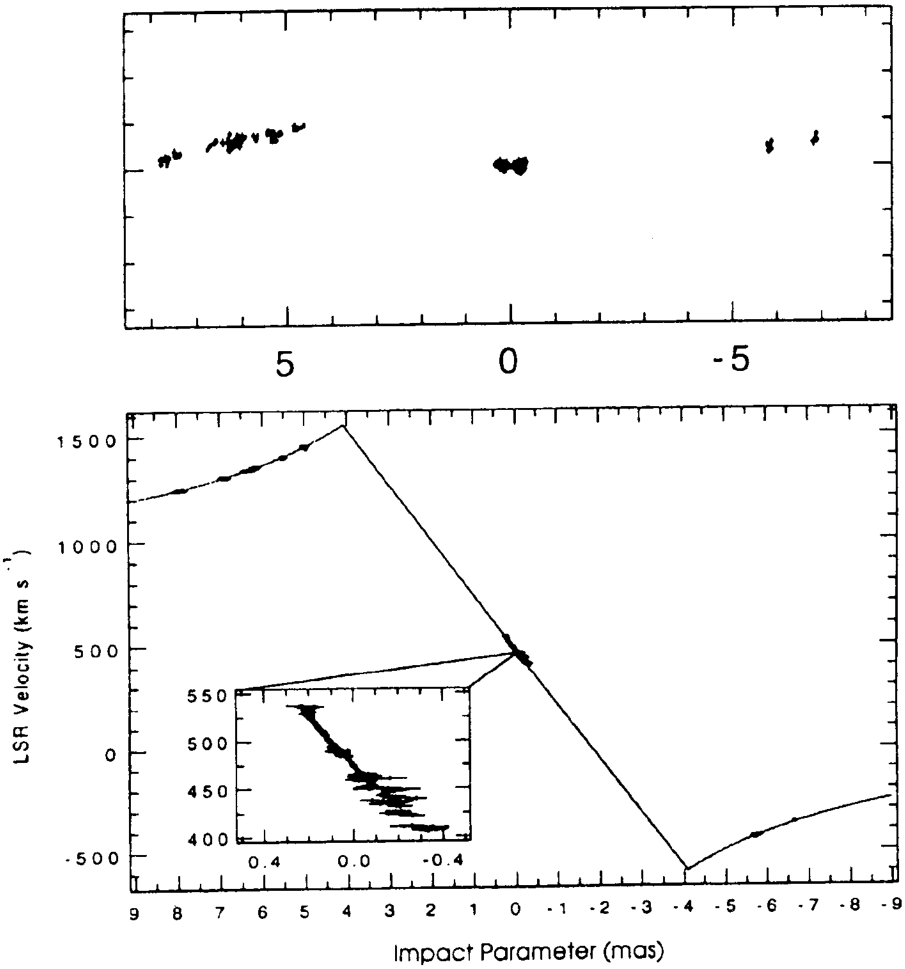


**Figure 1.** Top: Image of the maser emission from the nucleus of NGC 4258. The ticks on the axes are in milliarcseconds. One milliarcsecond coresponds to 0.035 pc, or $1.1 \times 10^{17}$ cm, at the distance of 7.2 Mpc. Bottom: The line of sight velocities of the masers versus their position along the major axis. The curved portions of the plot precisely follow a Keplerian dependence (from Moran et al., 1999).

**Our Galaxy**: The second and thoroughly convincing evidence for a black hole is at the centre of our own galaxy. Although many have been advocating this for nearly two decades, there is now clinching evidence. This is largely due to the efforts of Genzel and Eckart at the Max Planck Institute in Garching, and Ghez in California. They have combined very beautiful diffraction limited speckle imaging with spectroscopy with the NTT and the VLT. They have studied the stellar dynamics of the central star cluster by measuring the proper motion and radial velocities of more than one hundred stars. This analysis shows that the overall stellar motions are very close to being ISOTROPIC. This is consistent with a spherical star cluster. To illustrate these very beautiful observations we reproduce in figure 2 two images of the central star cluster surrounding SgrA* taken five years apart (Eckart et al. 2001). The arrows in the 1994 image indicate the direction and magnitude of the proper motion velocity. Their end points are the positions of the stars in 1999.

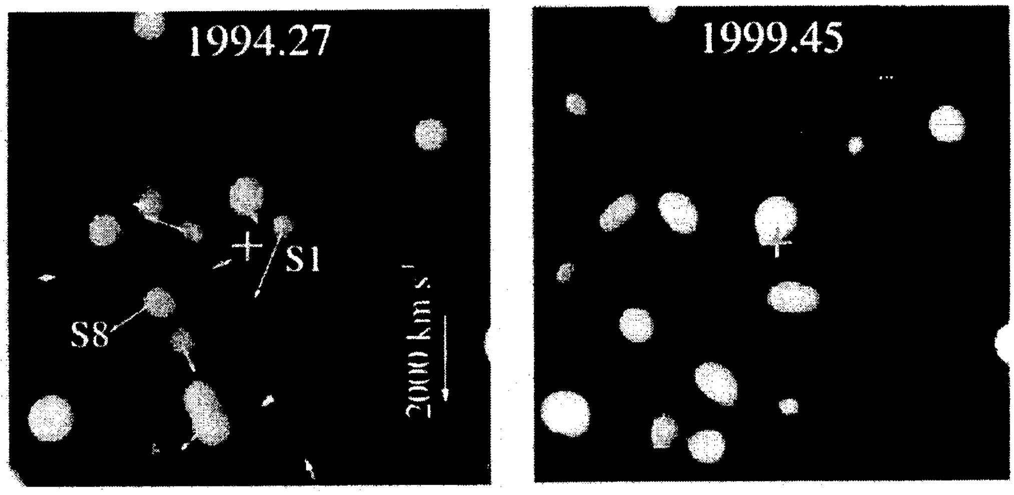


**Figure 2.** Two images of the central star cluster surrounding Sgr A* taken five years apart. The arrows in the 1994 image indicate the direction and value of the proper motion velocity. Their end points are at the current positions of the stars in the 1999 image (Eckart et al. 2001).

Recently, Ghez and her collaborators have used the Adaptive Optics System on the KECK telescope to take observations to a new realm. With relative positional accuracies of ~ 3 milliarcsec, they have been able to determine, for the first time, accelerations! Figure 3 shows this. The magnitudes of the two-dimensional acceleration vectors are:

$$\text{S0-1: } 1.2 \text{ mas } yr^{-2} \text{ or } 0.15 \text{ cm } s^{-2}$$

$$\text{S0-2: } 2.7 \text{ mas } yr^{-2} \text{ or } 0.33 \text{ cm } s^{-2}$$

Incredibly, it is now possible to explore individual orbits! Ghez and her collaborators have demonstrated the motion of these two stars can be fit by bound orbits around a central mass of $2.6\times10^6 M_\odot$ (Figure 4). Since these observations go down to a distance ~ 0.01 parsec, the implied mass density is $> 10^{12} M_\odot \mathrm{pc}^{-3}$! *This virtually rules out all other possibilities except a massive black hole*. This remarkable conclusion apart, these are incredibly beautiful observations.

Although these are the only two cases where there can be no reasonable doubt, circumstantial evidence is mounting from a variety of observations for supermassive black holes at the centres

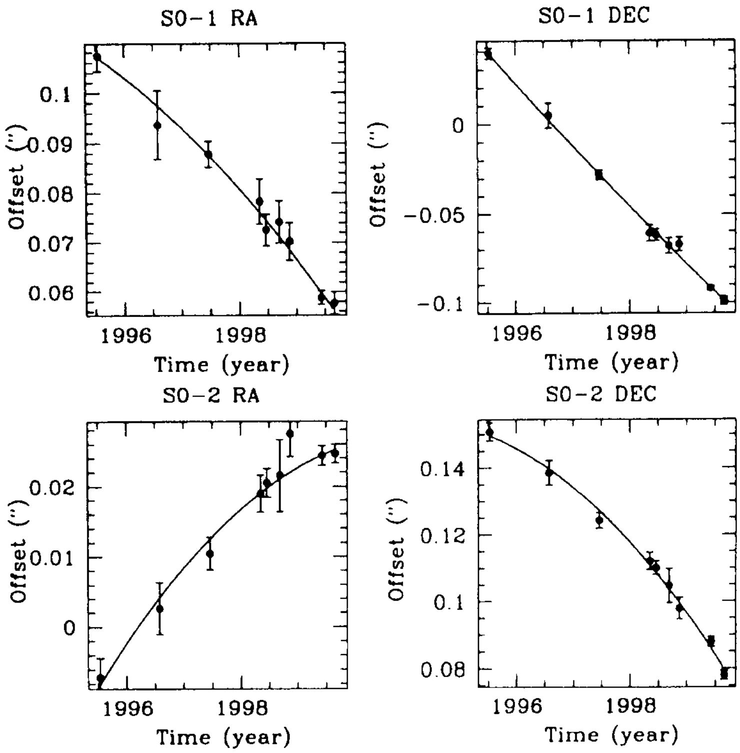


**Figure 3.** East-West and North-South positional offsets from the nominal location of Sgr A* are plotted as a function of time for the two stars SO-1 and SO-2. The solid line in each plot shows the model used to assess the acceleration term. Both the magnitude and direction of the acceleration are consistent with a $2.6 \times 10^6 M_\odot$ located at Sgr A* (from Ghez et al. 2001).

of most galaxies. The observations that have contributed to this conclusion include:

- HST photometry
- HST spectroscopy
- Ground-based long-slit spectroscopy
- Maser Observations
- Reverberation mapping etc.

Not only is this evidence getting stronger, there is even an apparent correlation between the mass of the central black hole and the luminosity of the bulge. This is shown in figure 5.

With an assumption regarding the mass-to-light ratio, this can be interpreted as a correlation between the mass of the black hole and the mass of the bulge. The different symbols indicate the

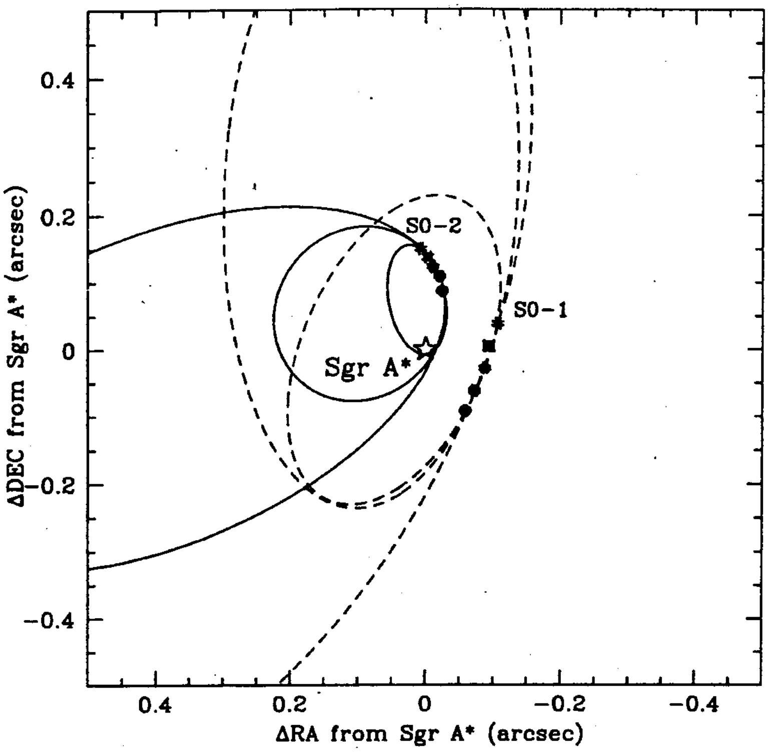


**Figure 4.** A 1" × 1" region, centred on the nominal position of Sgr A*, showing the motion of SO-1 & SO-2 and possible orbital solutions (Ghez et al., 2001).

different methods used. The sloping solid line is a particular model with $M_H$=0.005 $M_{\rm Bulge}$. The dashed line represents the following. Because quasars were populous in the early Universe, and have mostly died out now, the Universe must be populated with relic black holes whose average mass density $\rho_u$ matches or exceeds the mass equivalent of the energy $u$ radiated by the quasars. This was first pointed out by Choksi and Turner (1992). The integrated co-moving energy density in quasar light is $1.3\times10^{-15}$erg cm$^{-3}$. The corresponding present-day mass density, for a radiated efficiency $\epsilon$, is

$$\rho_u = \frac{u}{\epsilon c^2} = 2\times10^5\left(\frac{0.1}{\epsilon}\right)M_\odot\ Mpc^{-3} \tag{2}$$

This density can be compared with the luminous density in galaxies,

$$j = 1.1\times10^8 L_\odot\ Mpc^{-3} \tag{3}$$

This will give a ratio for the mass in relic black holes to light of galaxies:

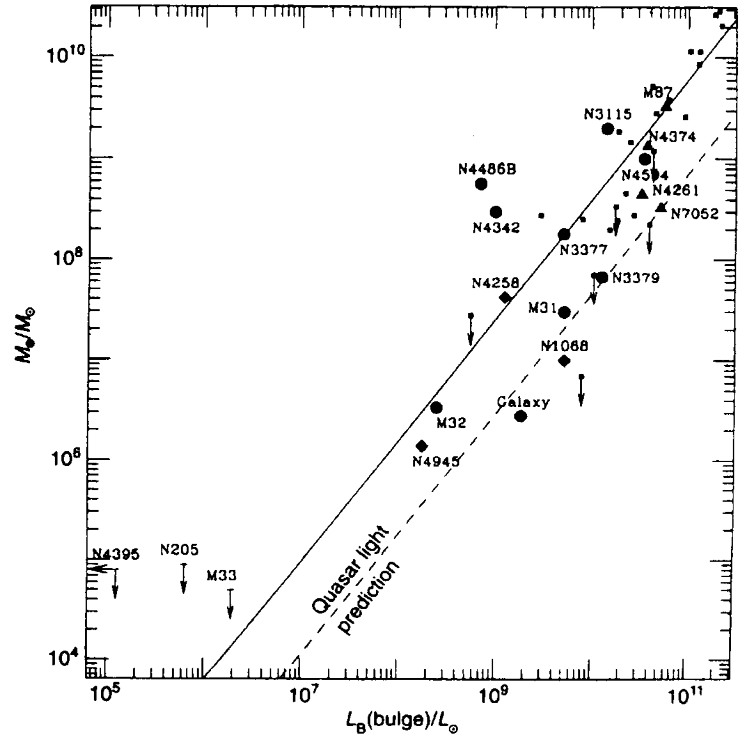


**Figure 5.** Mass estimates of the candidate massive black holes in galaxies with dynamical information plotted against the bulge luminosity of the host galaxy. The solid line is a model with $M_{BH} = 0.005 M_{\rm bulge}$ and $M_{\rm bulge} = 5(\frac{L_{\rm bulge}}{10^9 L_\odot})^{1.2}$. The broken line is the quasar light prediction (from Richstone et al., 2001).

$$\frac{\rho_u}{j} = 1.8 \times 10^{-3} \left(\frac{0.1}{\epsilon}\right)\left(\frac{M_\odot}{L_\odot}\right) \tag{4}$$

The broken line in figure 5 is this prediction.

I should stress that the trend seen in the figure may change as more data points are added. To illustrate this, I show in figure 6 a more recent plot of mass of the black hole versus the bulge luminosity (Gebhardt 2001). The point to be noted is that the relation between black hole mass to galaxy mass has decreased with inclusion of newer data. Basically, the masses of black holes have come down. So the last word has not been said!

Before leaving this topic, it is relevant to point out that in all cases where there is evidence for a central black hole, the galaxies have identifiable spheroidal components. This would suggest

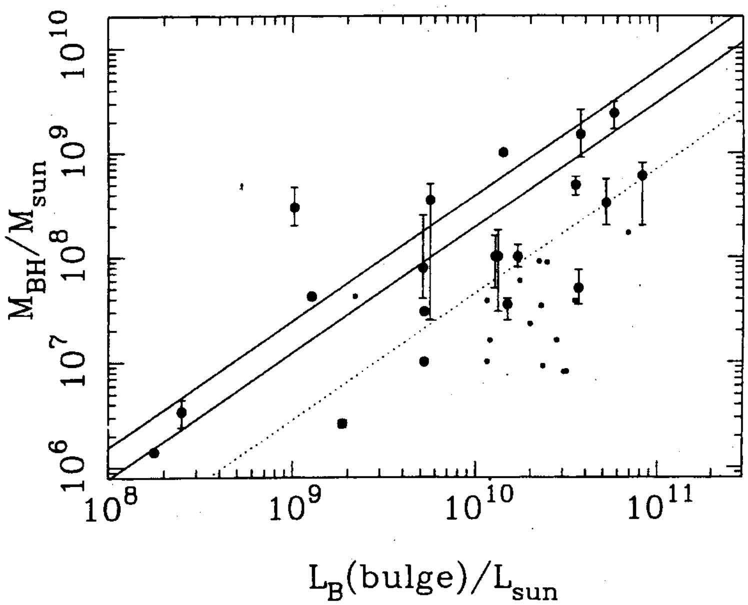


**Figure 6.** Black hole mass versus the luminosity of the bulge. The error bars represent 68% confidence. The small points without error bars come from reverberation mapping (Gebhardt 2001).

that black hole formation may be linked to the formation of the spheroid. It is also interesting that several well studied low-z quasars do not seem to be identified with spheroids.

Before proceeding further, one may reasonably ask the following question. Since none of the observations have probed gas motions or stellar motions to distances of the order of the Schwarzschild radii for the implied mass, how can we be sure that the central mass is a black hole rather than a star cluster? The reason is the following (Maoz 1995). A star cluster of mass $M$ and radius $r$, consisting of $N$ bodies, will either collapse or evaporate on a timescale of a few hundred two-body relaxation times

$$t_{\rm rel} = 0.14N\left(r^3/GM\right)^{\frac{1}{2}} [\ln(0.4N)]^{-1} \quad (5)$$

Of course, the lifetime of this cluster can be made longer than the age of the Universe by making the stars sufficiently light and thus numerous. In the galaxy NGC 4258, and also our Galaxy, **this would require a cluster with stellar masses less than** $0.1M_\odot$ - in other words, **brown dwarfs or white dwarfs**. However, these dwarfs with such low mass would be so large that they would rapidly collide and coalesce. The only other possibilities are small black holes or elementary particles. The problem is one doesn't know how to make black holes of mass $\sim 0.1M_\odot$! As for the exotic non-interacting particles, since they will be poor radiators they will not settle down to a condensed configuration.

*To summarize, although the observational evidence may still admit other possibilities, a massive central black hole is the most compelling and at the same time the most conservative hypothesis!*

**Why isn't every galaxy a quasar?!**
If virtually every galaxy has a massive black hole at its centre then why isn't every galaxy a quasar or one of the many varieties of *active galaxies*. In other words, why isn't there an ultra luminous source at every galactic centre?

Luminous manifestation of black holes is due to accretion of gas on to the hole. Now there are two possibilities

1. Feeding the black hole may be episodic. There is now ample evidence that merger of galaxies is quite common. *It is conceivable that gas accretion is restricted to periods soon after such mergers.*
2. But there is another possibility that is currently fashionable. When gas spirals inwards in the accretion disk and eventually falls into the black hole, the energy that is radiated is the gravitational binding energy as the matter falls into the deep potential well. Under certain conditions, the infalling matter can advect the liberated energy into the black hole! Such an advection-dominated accretion can occur at both high as well as low, mass inflow rate (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994; Begelman 1979; Begelman & Meier 1982). When the accretion rate is very high then the radiation is "trapped" in the matter, resulting in a poor radiation efficiency. In contrast, when the accretion rate is low matter may not be able to cool and radiate. Another way of saying this is the following. Much of the thermal energy is stored by the ions. If the ions are not able to transfer this thermal energy to the electrons then the radiation efficiency will be low.

In an alternative scenario inflow of matter due to accretion is coupled with an outflow at large distances. Such an outflow will carry away much of the mass, angular momentum and energy. (Blandford & Begelman 1999)

To summarize, even if every galaxy has a central black hole, the rarity of quasar-like manifestation can be accounted for by invoking such advection dominated inflows, or a variant of this in which the inflow is necessarily related to a mass ejection in an outflow. But I should stress that this is still a very open question, and the last word has not been said!

**The formation of massive black holes**: Let us now turn to the intriguing question of the formation of such supermassive black holes. Not only there are many routes, all these routes may be important depending upon the redshift we are considering.

One possible route is the following: Triggered by star formation a giant gas cloud in a young galaxy can collapse to a dense star cluster. Stellar coalescence will result in clusters of massive stars ($\sim 100M_{\odot}$). Supernova explosions will turn this into a cluster of neutron stars and/or stellar mass black holes. It is a distinct possibility that the gas ejected in supernovae will radiate away a significant amount of binding energy and allow this cluster of compact stars to contract to a relativistic cluster. Once a relativistic cluster forms, it can collapse due to a variety of relativistic instabilities or through emission of gravitational radiation. The result will be a supermassive black hole. This scenario is depicted in figure 7 which has been adapted from Rees (1978)

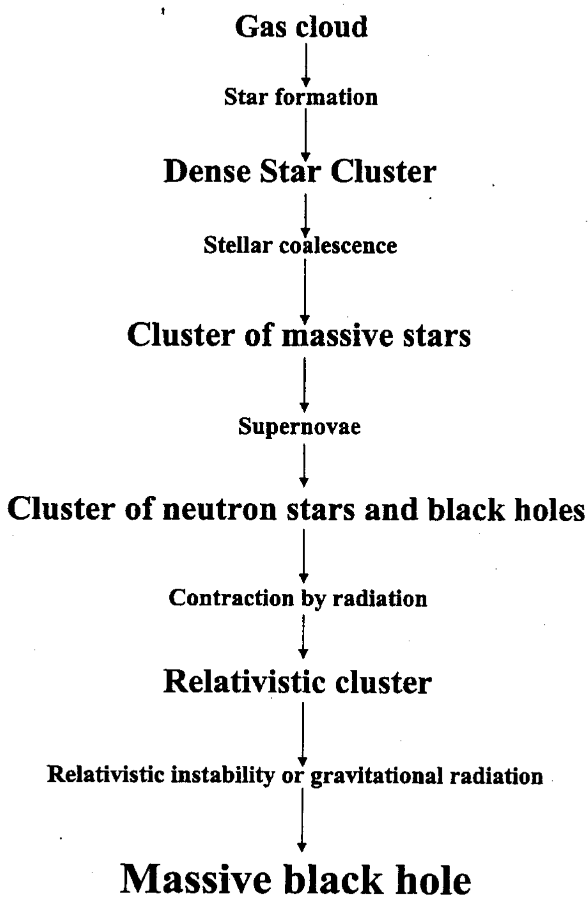


**Figure 7.** A possible route for the formation of massive black holes (adapted from Rees 1978).

In an alternative scenario (fig. 8), the gas cloud escapes star formation and contracts to a supermassive star. As was pointed out by Eddington and Chandrasekhar a long time ago, such a massive self-gravitating body will be essentially be supported by radiation pressure; gas pressure is unimportant. Indeed, this is expected to be the case for all stars with mass greater than $\sim 100 M_{\odot}$. But why would star formation be inhibited? As the gas evolves to higher densities and more violent internal dissipation, radiation pressure would prevent fragmentation. Another reason may be the magnetic field. Although, dynamically unimportant, magnetic field can prevent fragmentation. Unlike in the present-day cold molecular clouds, the free electron concentration may never drop to a low enough value as to allow ambipolar diffusion (Rees, 1993; Haehnelt and Rees 1993).

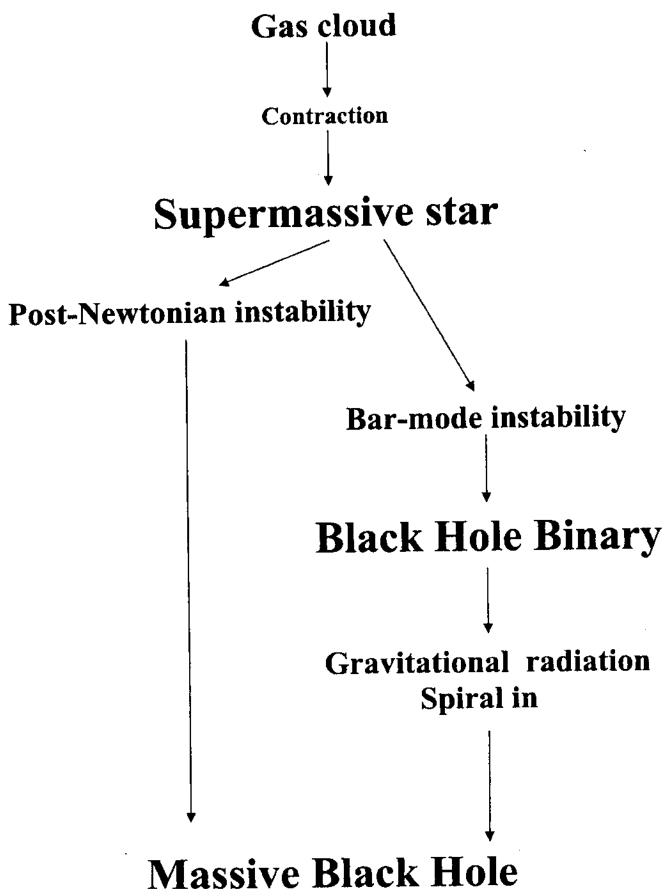


**Figure 8.** An alternative scenario for the formation of massive black holes (again adapted from Rees 1978).

Once such a superstar forms, it would continue to contract and deflate. Some mass could be shed in the process, which will carry away angular momentum and assist the collapse. Such a superstar will essentially be supported by radiation pressure. As was argued by Chandrasekhar soon after the discovery of quasars, such radiation pressure supported star would be unstable due to post-Newtonian instability (Chandrasekhar 1964). This may be understood as follows. *In Newtonian physics, for a star to be stable the pressure-averaged adiabatic index should be greater than* $\frac{4}{3}$, with $\gamma = \frac{4}{3}$ representing neutral stability. For a radiation pressure supported star the adiabatic index is close to $\frac{4}{3}$. *In General Relativity the critical value of* $\gamma$ *is greater than* $\frac{4}{3}$. This is because in GTR all forms of energy contribute to gravity, and in this sense gravitational effects are stronger than in Newtonian theory. The stability limit in GTR was first calculated by Chandrasekhar. In the post-Newtonian limit it reads as follows

$$\gamma_c = \frac{4}{3} + K\frac{R_s}{R} \tag{6}$$

where $R_s$ is the Schwarzschild radius and $K$ is of the order unity. What is interesting is that this instability will set in when the radius of the star is several thousand times the Schwarzschild radius. *To summarize, in this alternative the gas will directly collapse to a massive black hole.* Haehnelt and Rees (1993) estimate that the mass of the black hole could be about 20% of the original mass of the cloud. In this scenario, the mass of the hole will depend on the mass of the host galaxy, although they need not be exactly proportional to one another. The main difficulty is that this post-Newtonian instability may be suppressed by the angular momentum of the superstar, which can give it rotational support. The superstar will have to be clever and find ways of shedding its angular momentum. While there is no definitive answer to this, this route is not only very plausible but attractive from the point of view of explaining the high-redshift quasar population: one doesn't have to "grow" a massive black hole from stellar mass black holes.

Since this is an important point, let us digress a little and discuss this scenario in greater detail. The problem arises in the context of the high redshift quasars. The most remarkable feature of the quasar population is that it declines sharply between $z = 2$ and the present epoch of $z = 0$. On the other hand, during the past 10 years or so a large number of quasars have been found at $z \sim 4$. Although there is a hint that the co-moving density declines beyond $z > 3.5$, this is still controversial. These high redshift quasars pose a problem for the following reason. The highest redshift quasars formed when the Universe was only $\sim 10^9$ years old. So we have to form our massive black hole which presumably powers the quasar in a hurry!

There is a more interesting problem. While the highest redshift of quasars has gone up, the estimates of the redshift of the epoch of galaxy formation has come down. This is a direct consequence of the realization that galaxies are more extended and diffuse than previously believed.

At $z = 5$, the cosmic expansion time scale is long compared with the dynamical time scale within the luminous part of a typical galaxy. But it is NOT long compared to the time scales for the extended halos. The free-fall time from a radius $r$ is $\sim 10^9(r/100\text{ kpc})$ years.

The angular momentum of galaxies is believed to have been acquired by tidal interactions with neighbours at the epoch of turn around. But this can only impart a transverse velocity $\sim 5-10\%$ of what is needed for rotational support. This means that the material that is now at 10 kpc from the centre of the galaxy must have fallen in from $\sim 100$ kpc (consequently speeded up) and then cooled down. **Therefore, at $z \sim 5$ galactic halos would not have virialized, and the rotationally supported disks would not have developed!**

To summarize, the moral of the high-z quasars is that one cannot wait till galaxies form to virialize the massive black holes that power the quasars that we now find at the centres of the galaxies!

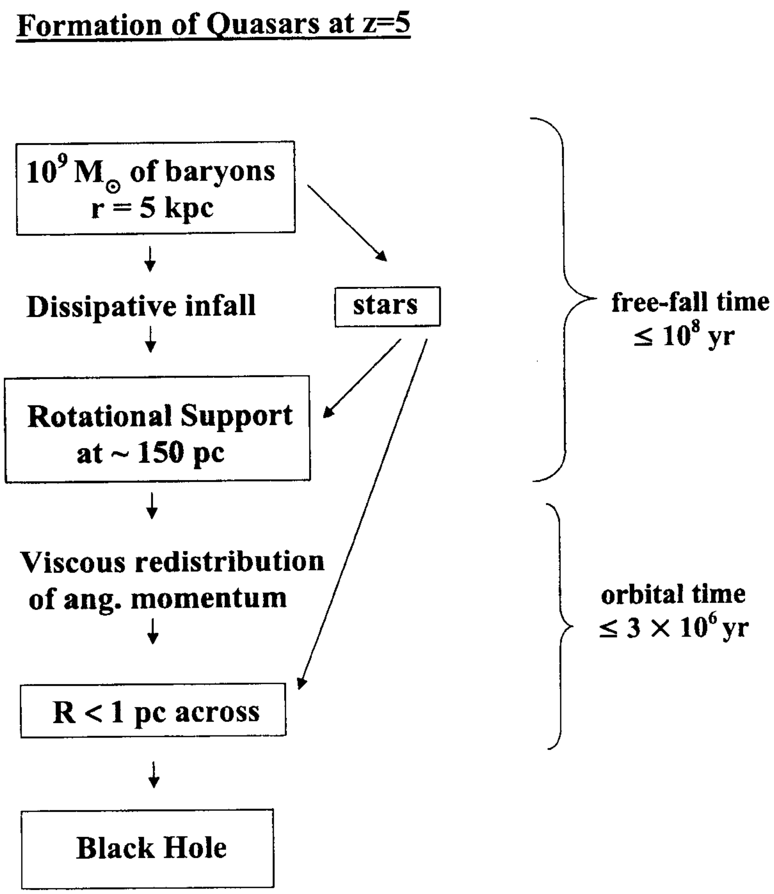


**Figure 9.** A schematic of what might happen in the central region within a bound halo of $10^{11} - 10^{12} M_\odot$ The possible evolution of the central $10^{10} M_\odot$ (with $10^9 M_\odot$ of baryons) condensing around an exceptionally high-amplitude peak in the initial density distribution is depicted (from Rees, 1993).

While the details are not clear, the flow diagram shown in figure 9 adapted from Rees (1993) highlights the crucial steps. The earliest quasars must form as soon as a sufficiently massive and deep potential well virializes. Let us, to be specific, assume $10^9 M_\odot$ of baryons are trapped in such a potential well. The radius of the sphere would be ~ 5 kpc.

The free-fall time scale from 5 kpc is < $10^8$ years. The tidally induced angular momentum of this material would be enough to provide centrifugal support at a distance ~ 150 pc from the centre. The dynamical time scale at this radius is $\sim 3 \times 10^6$ years. The question is how fast can this shed its angular momentum and become really compact. It has to do this in < 100 orbital periods, i.e. $3 \times 10^8$ years. Otherwise one cannot form a quasar at $z = 5$!

The answer to this question is not clear. But there are several types of viscosities that might help our cloud to get rid of its angular momentum

1. Gravitational instabilities: If star formation is quenched, the gas cloud would be strongly self-gravitating. And given its maximal rotation, it would be susceptible to non-axisymmetric instabilities. These would be extremely efficient in redistributing angular momentum in just a few orbital time periods.

2. Gaseous Viscosity: The usual type of viscosity, like in accretion disks, will also be operative. In addition, supernovae would stir up the gas and bulk random motions will set in. These processes can also dissipate away the angular momentum.

Although the last word has not been said, the only stumbling block is the formation of low mass stars that will in effect lock up the gas (such stars will neither expel or recycle the gas in $3 \times 10^8$ years). If one excludes this possibility then it is conceivable that the original cloud of baryons will condense to a size of a few parsecs. And once this happens, post-Newtonian instability will set in and the cloud will collapse to a supermassive balck hole.

**The signature of a black hole**: The forgoing discussion leads one to the conclusion that most galaxies have giant black holes. And these will be at their centres because a heavy object will spiral towards the centre due to **dynamical friction**. The evidence in support of this so far has been kinematical and dynamical. It would be satisfying if, in addition, one could deduce some clear signature of the black hole. Although the present observations of our Galaxy and NGC 4258 have ruled out all other possibilities, it is worth remembering that even the innermost maser spot in NGC 4258 is around $10^5$ Schwarzchild radii. These measurements tell us nothing about the region of strong gravity where General Relativity makes specific predictions. Indeed, while General Relativity has been spectacularly verified in the weak field limit - the solar system and the Hulse-Taylor Binary Pulsar - there is no test, as yet, in the strong field regime.

Some years ago, one didn't refer to black holes in polite company. Today we talk of John Mitchel and Laplace as having predicted black holes. One has almost forgotten Einstein! It is important to bear in mind that when one talks of black holes in an astronomical context, one is referring to black holes of General Relativity. One is referring to Kerr black holes. So one must not be satisfied with merely ruling out all other possibilities. One must look for evidence for black holes with the precise Kerr metric. Can we hope for this? We should be able to if we detect radiation that emanates from the innermost regions of the accretion disk. It is obvious that the gas in this region will be very hot with much of the gravitational energy released stored as thermal energy. Therefore, x-ray emission is the most direct probe of the region of relativistic gravity. How the inner regions of the accretion disk around a black hole would look was calculated thirty years ago by Bardeen and Cunningham (1972). This was pursued two decades later by several astrophysicists; what made them revisit this seminal work was, of course, the possibility of x-ray spectroscopic study of the accretion flow. In one of the prevailing models of AGN, the accretion disk is surrounded by a hot corona. The hard radiation from the corona is scattered by a geometrically thin but optically thick disk. The scattering will be predominant in the fluorescence lines, for example, the K-alpha line from iron. Such a line in the scattered radiation is expected to show a narrow blue wing, Doppler boosted in intensity, and a broad wing on the red-ward side shaped by a combination of transverse Doppler shift and gravitational red shift (Fabian et. al. 1989). The 6.4 keV fluorescence line of Fe with a profile just as mentioned has recently been detected by the Japanese x-ray astronomy satellite ASCA (Figure 10).

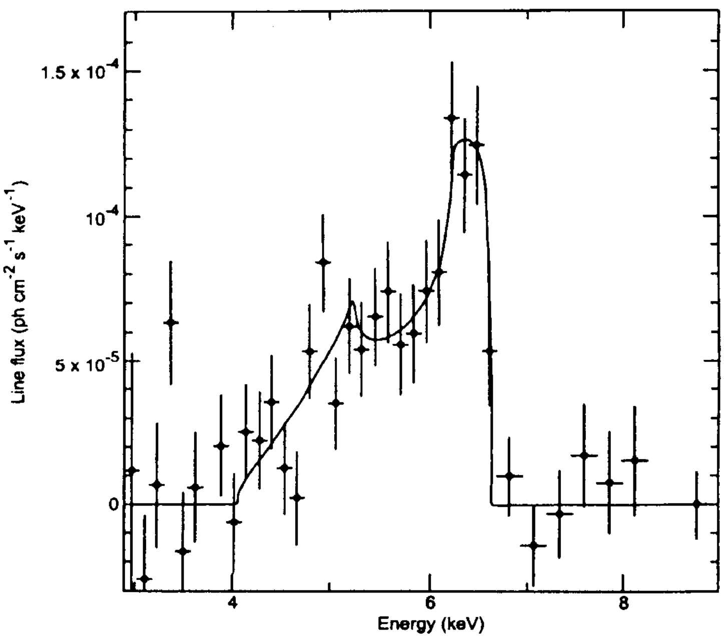


**Figure 10.** The Fe K-alpha line in MCG-6-30-15 (Tanaka et al., 1995). This clearly substantiates the theoretical expectation of a narrow blue wing boosted in intensity by the radial Doppler shift, and a broad red wing shaped by a combination of gravitational redshift and transverse Doppler shift.

The Doppler width of this line implies a velocity of 1/3 the speed of light! There is simply no doubt that one is seeing the effects of the central black hole. One can say with confidence that one is entering an era in which one can not only provide direct evidence for the existence of a black hole, but actually study it: the spin of the black hole, and indeed the metric of space-time itself around the black hole! With the Chandra and XMM telescopes one is already in a position to extend and refine the ASCA observations. Looking ahead, when ZEUS and CONSTELLATION are up one will be able to do ultrahigh resolution observations with unprecedented sensitivity.

In the ultimate analysis, the cleanest probe of the metric around a black hole would be to measure and map the polarization of x-rays. It is appropriate to recall what Chandrasekhar wrote in this context.

> *"Perhaps, I may digress here to indicate how one may eventually have a confirmation of the space-time around a rotating Kerr black-hole. If one imagines a Kerr black hole with an accretion disc of free electrons in the equatorial plane, then the polarization of the light emerging from it, after traversing the strong gravitational field of the black hole, will manifest so nonuniform a distribution that one should be able to map it. Will Nature be generous enough to provide a clean example which will enable such a mapping?"*

While this may be some decades away, there are more realistic possibilities during the coming decade. With telescopes like ZEUS and CONSTELLATION one would be able to study the seismology of the accretion disk. As we know, disks can support vibrational modes. Like in the case of stars, the frequencies of these modes can be used as probes of the structure of the inner disk. The lowest g-mode frequency is close to the maximum value of the radial epicyclic frequency $k$. In the Newtonian domain, this is equal to the orbital frequency. It drops to zero at the innermost stable orbit. It has a maximum value at $R = 4.5\,R_s = 9GM/c^2$ for a Schwarzschild hole. For a Kerr black hole, $k$ peaks at a smaller radius, and higher frequency, for a given mass of the hole. The frequency is 3.5 times higher for a maximally Kerr black hole with $(a/m) = 1$ than for a Schwarzschild hole. The point I wish to make is that one is not far away from being able to study such modes of the accretion disks around black holes. One may have already detected such modes in the microquasar GRS 1915 + 105. The QPO at 67 Hz may be related to the hotter inner part of the disk. The exciting thing is that such studies may help us to infer $(a/m)$ for holes whose masses can be independently determined (Kato and Fukui 1980; Novak and Wagoner 1992,93).

To recall, we have been discussing the possibility of studying the structure of space-time near the central black hole, for this would give us a verification of the General Theory of Relativity in the strong field regime.

In this context, nothing can be more satisfying than the detection of gravitational radiation from black holes, for this offers impressive tests of General Relativity involving no physics other than that of spacetime itself.

Unfortunately, the formation of black holes from direct collapse of gas clouds does not offer good prospects. The emission of gravitational waves will be most intense if the holes formed on a time scale $\sim R_g/c$, where $R_g = 2GM/c^2$. But as already mentioned, if the gas cloud collapses to a black hole then it is most likely to do so due to post-Newtonian instability. And this will occur at a large radius - several thousand times the Schwarzchild radius. So a monolithic collapse is not very promising from the point of view of detecting gravitational waves.

On the other hand, once such massive black holes form in the early history of galaxies, this will grow even bigger when galaxies merge - the two black holes will spiral towards one another and eventually coalesce. At that moment there will be an intense burst of gravitational radiation, in which ~ 10% of the rest mass will be radiated away in a time scale ~ $R_g/c$. The frequency range in which this energy will be concentrated will be around a millihertz. Unfortunately, this is too how a frequency for ground-based detectors such as LIGO. Below ~100 Hz ground-based detectors have poor sensitivity due to seismic noise, weather noise(!) etc. So space-based detectors are needed.

The European Space Agency, in collaboration with NASA, is currently building a **Laser Interferometer Space Antenna (LISA)**. This will consist of 3 spacecrafts placed in a solar orbit at 1 A.U., trailing the earth by 20 degrees. The spacecrafts will be located at the corners of an equilateral triangle with sides of 5 Million kilometers! Two arms of the triangle comprise a Michelson interferometer with vertices at the corners. The third arm permits another interferometric variable to be measured. The interferometers will use the same 1 micron light as the terrestrial detection, but will need only a single pass to gain the desired sensitivity. The end points of the interferometers will be referenced to proof masses free-floating and shielded by the spacecraft.

The good news is that LISA is scheduled to be launched in 2011. LISA will have unprecedented sensitivity to detect the gravitational radiation from coalescing massive black holes. The bad news is that the merger rate of large galaxies with supermassive black holes is only about one event per century! But the merger of smaller galaxies may be more frequent, and the current estimates suggest that LISA should be able to detect one event per year.

What we have mentioned so far concerns the merger of two massive black holes. LISA will be so sensitive that it could detect nearly periodic gravitational waves from stellar mass objects orbiting a $10^6 M_\odot$ black hole, even at a hundred megaparsec. This is remarkable because the amplitude of the wave will be reduced by a factor $m^*/M_{\mathrm{hole}}$ compared to the case where two massive holes coalesce. But they will have to be compact stars such as white dwarfs, neutron stars or stellar mass black holes. The point is that normal stars will be tidally disrupted before they get into a relativistic orbit. Therefore, it will have to be a condensed star, such as white dwarf or a neutron star.

The orbit of a compact star in a relativistic orbit around a massive black hole will precess. The gravitational waves, modulated by orbital procession, will carry information about the spacetime metric (Rees 2001).

To summarize, LISA offers exciting possibilities of directly inferring the metric around the central black holes that populate the galaxies.

In the 1970s Chandrasekhar wrote *"Astronomy is the home of General Relativity"*. Twenty years later he was to say *"General Relativity is the home of astronomy"*. In the 1920s Edwin Hubble wrote a famous book entitled *"The Realm of the Nebulae"*. Had he been alive today, he would have called the book "The Realm of the Supermassive Black Holes". For it is turning out that the countless number of galaxies in the Universe have massive black holes at their centres. Although one can never hope to give a simple, elegant description of galaxies, like for the world of elementary particles, one can do better with respect to the centres of galaxies - one can give an **exact description**. Let me, therefore, end with a quotation from Chandrasekhar:

> *"Black holes are macroscopic objects with masses varying from a few solar masses to millions of solar masses. To the extent they may be considered as stationary and isolated, to that extent, they are all, every single one of them, described exactly by the Kerr solution. This is the only instance we have of an exact description of a macroscopic object. Macroscopic objects, as we see them all around us, are governed by a variety of forces, derived from a variety of approximations to a variety of physical theories. In contrast, the only elements in the construction of black holes are our basic concepts of space and time. They are, thus, almost by definition, the most perfect macroscopic objects there are in the universe. And since the general theory of relativity provides a single unique two-parameter family of solutions for their description, they are the simplest objects as well".*

> *"In my entire scientific life. . . . . the most shattering experience has been the realization that an exact solution of Einstein's equations, the KERR METRIC, provides the absolutely exact representation of untold numbers of massive black holes that populate the Universe".*

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