PART III

NUCLEI

GALACTIC NUCLEI AND COMPACT SUPERMASSIVE OBJECTS

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Abstract. This is a review of the observational evidence concerning compact supermassive objects, their formation and evolution, and their dynamical interaction with dense stellar systems in galactic nuclei.

> *All these have never yet been seen –*
> *But Scientists, who ought to know,*
> *Assure us that they must be so...*
> *Oh! let us never, never doubt*
> *What nobody is sure about!*
>
> Hilaire Belloc, 1910.

One of the reasons galactic nuclei are so interesting is that they provide an arena for a remarkable range of physical problems. Radiation, gas, dust, magnetic fields and compact objects all interact in a rich variety of ways in different regions of the nucleus. The energy densities of radiation, gas, dust and magnetic fields cover many orders of magnitude; the forms of compact objects may include black holes, neutron stars, white dwarfs, supermassive objects and even ordinary stars.

Among all these interactions, it is probably fair to say that gravitation is the most basic in that it determines the overall structure and evolution of the galactic nucleus. Indeed, it is the gravitational contraction of the whole system, or parts of it, that ultimately drives most other forms of energy in the nucleus. Rather than repeat recent general reviews of gravitational interactions and other problems in galactic nuclei (Saslaw, 1973, 1974), I'd like to try to review one major question which the observations have raised more and more insistently during the last year or two: what is the dynamical relation between galactic nuclei and compact supermassive objects?

As a working definition of compact supermassive objects, we may suppose that their mass is $\gtrsim 10^3\,M_\odot$, to distinguish them from stars, that they are gravitationally bound, and that their size is much smaller than the size of the galactic nucleus with which they are associated. This leaves open the nature of their structure and lifetime. They may be black holes or black holes surrounded by gaseous disks or satellite systems. They may be supermassive stars supported by gas, radiation pressure, rotation, or magnetic fields. They may be very small (e.g. relativistic) clusters of small mass stars. In principle there is no known reason why matter should not pass through any of these forms. Therefore, let us first ask:

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Hayli (ed.), Dynamics of Stellar Systems, 379–393. *All Rights Reserved.*

1. Is There Any Observational Evidence for Compact Supermassive Objects?

There are five main phenomena in which people have suggested looking for compact supermassive objects. These are quasars, galactic nuclei, Lacertids, jets near the centers of galaxies, and the components of extended extragalactic radio sources. Of course, there is also the possibility that all these phenomena, including quasars (Kristian, 1972), are manifestations of active galactic nuclei. If so, the discovery of these objects in one phenomenon would have important implications for all five of them. Let us consider each in turn.

1.1. QUASARS

After Hoyle and Fowler (1963) first proposed the existence of thermally supported supermassive stars in radio galaxies, they were quickly siezed upon as a possible energy source for quasars. After pulsars were discovered, more massive versions of stars supported by rotation or magnetic fields – spinars – were also suggested (Cavaliere *et al.*, 1971). These models could, in principle, be distinguished observationally from models in which quasars were powered by many small explosions (e.g. supernovae or colliding stars) or by multi-pulsar systems, if the massive objects produce periodic variations in intensity. Either a pulsation of the object, or a rotation which produces a pulsar-like beacon could be observed. This gave rise to a still inconclusive debate (e.g. Chertoprud *et al.*, 1973) about the existence of real short term periodicities in quasars, and particularly in 3C 273. Although there is no compelling evidence for periodicity, the absence of evidence does not rule out compact massive objects in the form of black holes surrounded by accretion disks or satellite systems, since these types of supermassive object need not have periodic intensity variations.

There is a second line of evidence in quasars which is also inconclusive at present. This is the possible physical connection between quasars and galaxies which are close together on the celestial sphere. Perhaps the best evidence for a physical connection is the apparent bridge (Arp, 1971) between Markarian 205 ($Z=0.07$) and the spiral galaxy NGC 4319 ($Z=0.006$). However, it is not clear whether this bridge is just a photographic effect of two images close together on the plate (Lynds and Millikan, 1972). A bridge may also join Markarian 205 to a stellar object 3″ away (Weedman, 1973). One can also argue for a physical association on the grounds that there are more geometric associations (about a half-dozen) than would be found statistically in a random distribution (Burbidge *et al.*, 1971). However selection effects make the meaning of this result very uncertain (Bahcall *et al.*, 1972; Hazard and Sanitt, 1972; Burbidge *et al.*, 1972). If a physical connection between galaxies and some quasars does turn out to exist, then there could be two types of quasar (Chio *et al.*, 1973). One class would be the more usual type of quasar at cosmological distance; the second, rarer, class would consist of massive objects ejected from their associated galaxies.

1.2. GALACTIC NUCLEI

The most intriguing galactic nucleus from the present point of view is the Seyfert

NGC 1275, which is identified with the strong (~ 50 fu) radio source Perseus A (alias 3C 84). This object is sufficiently peculiar to be interesting and sufficiently close (54 Mpc if $H = 100$ km s^{-1} Mpc^{-1}) to study in detail (Burbidge and Burbidge, 1965; De Young *et al.*, 1973). Very long baseline interferometry of the radio source in the nucleus (Legg *et al.*, 1973) shows it to consist of at least four components. Of course, VLB observations with one baseline do not give a unique picture of the source. In one model fit to the data, there are four sources, each a couple tenths of a parsec in size, stretching along a line about two parsecs long. Each source emits between 5 and 19 fu at ~ 3 cm. The other proposed model contains one strong resolved source, and four weaker sources (0.3–1 fu) with diameters less than 0.05 parsec. While this directly shows that powerful radio emitters ($\sim 10^{42}$ erg s^{-1}) can occupy small volumes, we need still higher resolution before we can understand the nature of these regions.

1.3. LACERTIDS

The Lacertids, named after their prototype BL Lacertae, are a peculiar class of objects characterized by a nearly stellar appearance, a continuous optical spectrum free of lines, optical and radio variability over periods of minutes to months, and a flat or inverted radio spectrum. At various times the Lacertids were suggested to be accreting neutron stars, accreting massive black holes in our Galaxy, and blue shifted quasars. However, the recent measurement (Oke and Gunn, 1974) of a redshift of 0.07 in the fuzz surrounding BL Lacertae suggests that it is associated with the nucleus of a distant elliptical galaxy and radiates $\sim 10^{45}$ erg s^{-1}. These measurements are very difficult and still await confirmation. The Lacertid P1205-008 is separated by 10″ arc from a galaxy with $Z = 0.1$. (Condon and Jauncey, 1974). If the Lacertid and galaxy have same redshift, their separation is 30 kpc. The size of the Lacertid at 10 GHz, estimated from synchrotron self-absorption ($B \lesssim 1$ G) is $\lesssim 3$ pc, so the ratio of separation to size $\gtrsim 10^4$.

If this interpretation is correct, then the statistical association between Lacertids and galaxies discovered by Condon and Jauncey (1974) becomes very significant. Of the ten Lacertids for which precise radio positions were known, nine are associated with either well defined galaxies or, as in BL Lac, with surrounding nebulosity. Remarkably, several of these Lacertids are not in the center of their galaxies, but rather near the edge of the galaxy or within one or two galactic radii of the center. Thus Condon and Jauncey suggest that they were ejected from the nucleus of their parent galaxy. At present many more potential Lacertids are known, and when their precise radio positions are measured, we will see whether this association improves.

1.4. JETS

In a small number of galaxies a jet containing several optical condensations sticks out from the nucleus. The best studied case is the giant EO galaxy, M87. Even here, there is no answer to the fundamental question whether the jet is colinear, or just several objects scattered in a half-plane seen approximately edge-on. Unfortunately, statistical arguments are not much use because only a few jets are known and selection effects reduce the chances of seeing a disk of objects face-on (although one may be present in the other part of NGC 1275, Sandage, 1971). The optical knots in M87 are $\lesssim 20$ pc in radius (for $H = 55$ m s^{-1} Mpc^{-1}), and their ages are between about 10^4 yr. and 2×10^5 yr (for velocities between the escape velocity and c). The most recent analysis of their structure by Okoye (1973) shows that it is barely possible to stabilize them by inertial confinement if they are gas blobs with a temperature between $\sim 10^4$–10^5 K. If they are very hot ($T \gtrsim 10^7$ K), or not sufficiently dense, they may be confined by ram pressure if they are ejected with $v \approx c$ or if the magnetic field in the blob has its equipartition value. However such a magnetic field would lead to a lifetime of only $\sim 10^3$ yr for electrons generating optical synchrotron radiation, and some mechanism, not presently known, would be necessary to frequently replenish these electrons in the knot. If, on the other hand, the knots contained compact objects of mass $\gtrsim 10^7$ $M_\odot$, the problem of their stability and electron supply would be greatly alleviated, and perhaps even solved.

Perhaps somewhat related to jets, are cases where one galaxy may have ejected a nearby companion. Most of the evidence for this is due to Arp (e.g. Arp, 1972), but few astronomers are very convinced by it. However, there is a recently discovered peculiar object (Arp and O'Connell, 1975) which is rather intriguing from this point of view. The blue compact galaxy CG 1124+54 has a main body ~ 1 kpc long ($H = 50$ km s^{-1} Mpc^{-1}) consisting of a central core ~ 200 pc in radius with two fainter disturbed lobes on either side. About 1.6 kpc from the center, approximately along the major axis, is a companion object whose size in about 500 pc × 250 pc. The edge of this companion farther from the main compact galaxy is rounded and sharp; the closer edge is fainter and less well-defined. Both objects have a redshift of 2895 ± 32 km s^{-1}.

Two explanations for this configuration seem plausible. First, the companion may be gravitationally bound to the main body and we happen to be looking along the polar axis of their orbit. The peculiar structure of the object could then be caused by tidal stresses or by internal dust lanes. Second, the companion may have been ejected from the main body, distorting it in the process. In this case the radial velocity of both objects would be the same even if we are not observing the system perpendicular to the line of ejection. This is because a compact massive object would radiatively ionize the background gas around the main body, but would not drag much of this gas with it. High resolution spectrometry could determine whether the companion shows the turbulence and ionization structure expected for a massive object moving supersonically through surrounding gas (Saslaw and De Young, 1972).

1.5. EXTENDED RADIO SOURCES

In all the previous examples, except for jets, the evidence for ejection is at best circumstantial and at worst merely circumgalactic. In the case of extended extragalactic radio sources, however, there is general agreement that significant amounts of energetic material have been ejected from the nucleus of a galaxy. The main question is the form of the ejecta and the method of ejection. Until the last year or two, models of extended radio sources were dominated by the conventional picture in which an explosion in the nucleus ejects two masses of relativistic plasma in opposite directions, and the escaping plasma is confined by its ram pressure on the intergalactic gas. While this process may sometimes occur, the argument for its general applicability has run into four severe observational problems:

(i) Many radio galaxies contain very compact components. In 3C 390.3, for example, the ratio of the width of the smaller component at 5 GHz to its separation from the central galaxy is greater than 30 (Harris, 1972). In Cygnus A, perhaps the best studied extended source because of its proximity to us, a significant flux ($\gtrsim 20\%$) at 5 GHz from the main double components comes from compact regions $\lesssim 1$ kpc in scale, but the separation of these regions from the central galaxy is ~ 95 kpc. Neither inertial confinement of the plasma by cold gas, nor ram pressure confinement with the intergalactic gas seem adequate to produce such large ratios of separation to size (Hargrave and Ryle, 1974).

(ii) In most double radio sources, the radio components are aligned with the central galaxy to within 5°–10°. In Cygnus A, the compact components are aligned with the central source to within ~ 30 arcmin (Hargrave and Ryle, 1974).

(iii) When the central optical object is an elliptical galaxy, the main radio components have a strong tendency to lie approximately in the plane of the galaxy, rather than near the poles (Mackay, 1971; Bridle and Brandie, 1973). However, in models which eject gas from the galaxy, one would expect the ejection to occur near the poles, along the path of least resistance.

(iv) Perhaps the most severe problem for theories which eject a burst of plasma, is that the lifetime of the relativistic electrons to synchrotron radiation is usually considerably less than the age of the radio source. Examples are Cygnus A (Hargrave and Ryle, 1974) and the giant sources DA 240 and 3C 236 (Willis *et al.*, 1974) which have linear extents of 2.0 and 5.7 Mpc respectively. However this is a difficulty even for many smaller sources.

To meet these objections, two different major theories of radio source structure have arisen. In one, beams of low frequency radiation (Rees, 1971) or relativistic particles (Scheuer, 1974; Blandford and Rees, in press) stream continuously out of the nucleus of the galaxy. This can account for problems (i) and (iv), but has difficulties with (ii) and (iii). The second approach is to suppose that compact massive ($M \gtrsim 10^5$ $M_\odot$) objects are ejected from the nucleus of the galaxy (Burbidge, 1967; Saslaw *et al.*, 1974). The detailed nature of these objects is of secondary importance and there are a number of possibilities. They may be either spinars, supported by thermal, rotational and magnetic energy. They may be black holes surrounded by a disk of gas which is slowly accreted, or by a satellite system of smaller spinars or pulsars. They may even evolve from spinars into black hole systems. Any of these objects provides a natural solution to these four important observational problems. They store energy in compact regions (without adiabatic losses), they can be ejected in close alignment with the central galaxy and near the plane of this galaxy, and they can supply energy fairly continuously over long periods of time.

At present, none of the observational evidence for the existence of compact supermassive objects is really compelling, and a skeptic would probably be justified in doing nothing, or at least working on something else. Nevertheless, the promise of massive objects – and the problems of other explanations – are producing greater interest in their properties and relation to galactic nuclei. We therefore turn first to a brief review of the work which has been done on the formation and evolution of these objects, and then to their dynamical interaction with galactic nuclei.

2. Formation and Evolution of Compact Supermassive Objects

2.1. FORMATION

Not very much is known about the manner in which compact massive objects may form. However, if they form anywhere, it is likely to be in galactic nuclei where the density of gas and stars is high. One possible process is for a dense relativistic rotating disk of gas, released from stars either through normal evolution or collisions, to collect in the center of the nucleus and fragment into several objects (Salpeter, 1971). So far, no detailed calculations have been made to determine the conditions for nonlinear fragmentation, the masses of the fragments, or whether fragments fragment. The problem is one of the most intricate in astrophysics; star formation which is a special case seems almost simple by comparison.

A more calculable process for formation of these massive objects is stellar coalescence. If the nucleus of a galaxy contains a sufficiently dense stellar system, stars may often collide bodily. For a typical star the mean time between collisions is (Spitzer and Saslaw, 1966)

$$\tau_c = \frac{1}{n\sigma v} = \frac{9.7 \times 10^{21}\ R_{(\mathrm{pc})}^{7/2}}{N^{3/2}(m^{1/2}r^2/m_\odot^{1/2}p_\odot^2)\,(1 + 8.8 \times 10^7\ R_{(\mathrm{pc})}r_\odot/Nr)}\ \mathrm{yr}, \tag{1}$$

where r is the radius of the star. In deriving this relation, the virial theorem has been used and the geometrical cross section has been increased by a factor $(1+2Gm/rV^2)$ to account for the gravitational attraction, ignoring tidal deformation.

If the collisions are sufficiently energetic, the stars will dissolve into gas. The requirement for this to be possible can be estimated approximately in the case of a head-on collision. Most of the kinetic energy is converted into thermal energy, and substantial liberation of gas can occur if the total energy is positive. So if each star is a polytrope of index n,

$$\tfrac{1}{2}m\left(\frac{V}{2}\right)^2 - \frac{3}{2(5-n)}\frac{Gm^2}{r} > 0, \tag{2}$$

where V is their relative velocity at large separation. For two sunlike stars ($n=3$), this implies $V \gtrsim 1500$ km s^{-1}. This result is approximate since it does not include the effects of shocks and the time-dependent gravitational field. Next we describe the more exact results, first considering what happens when the relative velocities are so small that the bulk of the two stars coalesces (Ulam and Walden, 1964; Colgate, 1967;

Sanders, 1970; Seidl and Cameron, 1972). This problem is somewhat similar to the collision of two gaseous galaxies described by Alladin (this volume, p. 167).

If two similar stars collide at relative velocities exceeding several hundred kilometers per second, most of the gas will interact supersonically relative to the local sound speed, and shocks will convert much of the kinetic energy of stellar motion into thermal energy which is then radiated. Thus the collision is highly inelastic. If, moreover, the positive energy criterion of Equation (2) is not satisfied by a large margin, most of the stars' material will coalesce. The distended, newly-formed object pulsates for some time, and then settles down to a well-defined star. During the collision, the temperature and density are not great enough to generate an important amount of energy by thermonuclear reactions (Spitzer and Saslaw, 1966; Mathis, 1967).

The detailed hydrodynamics of coalescence is very complex; the only extensive treatment is for a star which smashes into its mirror image (Seidl and Cameron, 1972). This is a two-dimensional numerical study of the head-on collision of two polytropes of index 3 with solar mass and radius. As the encounter proceeds, the stars become squashed and a sheet of gas is heated then ejected in the plane perpendicular to the initial relative velocity. Simultaneously a recoil shock forms in the outer layers and ejects gas from the backs of the stars, an effect which is relatively more important at low collision velocities. Experiments for distant relative velocities of zero, 1000, and 2000 km s^{-1} showed that about 5%, 18%, and 60%, respectively, of the gas was liberated. Thus our rough estimate provides a surprisingly good criterion for disruption, especially considering the simple energy argument on which it is based.

Unfortunately, only a small fraction of collisions are head-on, and the rest must be handled gingerly by approximate methods. Sanders (1970) has applied simplified models of undeformed stars to collisions with relative velocities at infinity between 62 and 2356 km s^{-1}, impact parameters from head-on to grazing, and mass ratios from 1:1 ($M_{\odot}$) to 1:50 ($M_{\odot}$). In these models the two stars are divided into long rectangular tubes of gas parallel to their relative velocity. Each tube collides only with its geometric counterpart, and their changes are not coupled to the rest of the star. The collision converts the kinetic energy of the star's motion into heat, conserving linear momentum, and this thermal energy is divided between the two mass tubes in proportion to their kinetic energy before impact (relative to their own center-of-mass frame). If the thermal energy of a mass element is greater than its binding energy to the star to which it is most strongly bound, the mass element is assumed to escape.

Clearly the accuracy of these assumptions is very uncertain, especially for low-velocity collisions which may transfer substantial momentum perpendicular to the relative velocity of the gas tubes. For a head-on collision, at these low velocities, no mass would be lost on this approximation; therefore we would expect the approximation to become worse as the impact distance, p, becomes smaller. The general shape of the curve of mass loss as a function of p would then be zero for $p=0$ and for $p>2r$, with a maximum in between. As an example, Sanders' computations for two suns colliding with $V_{\infty}=62$ km s^{-1} give a total maximum mass loss of $\sim 0.04\ M_{\odot}$ at $p \approx 0.4\ r_{\odot}$.

What is the condition that the two stars coalesce? The collision converts kinetic energy from their orbital motion irreversibly into heat. If enough orbital energy is lost, the stars will become bound to each other and successive collisions will reduce the orbit's semimajor axis until most of the mass merges permanently. This occurs if the kinetic energy of motion which is converted into heat exceeds the orbital kinetic energy of the two stars at infinity. Without detailed computations it is not certain how much of the thermal energy is irreversibly lost, i.e. how inelastic the collision is. Sanders has assumed complete inelasticity, which maximizes the chance of coalescence. Then one can compute how much thermal energy is produced in each colliding mass tube, add up the total for all tubes, and see if this is enough to coalesce the stars.

In applying this procedure to stars of different mass, it is important to know the density distribution of the colliding stars. More massive stars will generally have lower average density than the less massive ones. Their density distribution will dominate the question of whether two stars of greatly different mass interact sufficiently strongly to convert enough orbital energy into heat so that they coalesce. Colgate (1967) first suggested that stars of $M \gtrsim 50\ M_\odot$ would not coalesce with the more numerous field stars of $\sim 1\ M_\odot$, but would simply have holes punched through them. Thus there would be an upper limit to the mass which could form by such coalescence. However, this estimate assumed that the coalesced star forms with the same binding energy per gram as its progenitors, and retains the same polytrope structure after relaxation so that in the new coalesced star $R \sim M$. On the other hand, Sanders (1970), assumed that $R \sim M^{0.7}$ and the density distribution in the relaxed coalesced star is homologous to the sun. Moreover, he also considered the effect of the gravitational field of the massive star in increasing the relative velocity of collision, resulting in greater heating of the gas tubes. The combined effects of these assumptions is that the ability to coalesce does not decrease so strongly with large mass ratios as in Colgate's calculation. This result is very important for the general evolution of the cluster.

Sanders' main result regarding the physics of coalescence is that, with the assumptions outlined above, two stars can coalesce at sufficiently small impact parameters provided that their relative velocity at infinity is less than a critical value. This critical velocity decreases as the ratio of the more massive to the less massive star increases. For example, with a mass ratio of 1:4, coalescence can occur if $V_{\mathrm{rel}} \lesssim 1800\ \mathrm{km\ s^{-1}}$, while for a ratio 1:50, $V_{\mathrm{rel}} \lesssim 1400\ \mathrm{km\ s^{-1}}$.

Stars are very nutritious. A large star can increase its longevity by swallowing a smaller one for two main reasons. First, of course, there is the added hydrogen fuel. Second, more hydrogen of the massive star is mixed throughout the core, increasing the main-sequence lifetime. Thus whether or not a massive star evolves into a supernova depends on the ratio of its coalescence-mixing time scale to its main-sequence lifetime in a given state. If the core of a coalesced star mixes faster than it burns, it may be possible to build up extremely massive stars in the center of the stellar system. This question begs an answer.

Having been swallowed, a star must be digested, then absorbed. The additional heat created in the collision distends the coalesced star beyond the normal size for its total mass. The bloated object pulsates awhile and eventually settles down to mechanical equilibrium after several relaxation times of order $(G\varrho)^{-1/2}$ (about 15 min for the Sun). However, the thermal energy has not yet been absorbed throughout the star, and for this to occur requires several photon diffusion periods, which entails a Kelvin-Helmholtz time scale of order GM/RL (about 10^7 yr for the Sun). The tone of these last two sections indicates that our present knowledge of the structure and evolution of the coalesced star is only qualitative. This represents one of the most important, and one of the most difficult, problems in our understanding of dense stellar systems.

As the stellar system evolves, there is a period during which the time scale for coalescing collisions to involve many stars becomes less than the time scale for these massive stars to evolve off their main sequence. If enough time is spent in this regime (before disrupting collisions take over) stars of extreme mass may form. At first the mass of a typical star is built up by coalescence with smaller stars. Every addition of hydrogen with mixing is assumed to be so effective that it sets the star's evolutionary clock back to zero (an important question for further calculation). In this way stars of $\sim 500\ M_{\odot}$ may form (Sanders, 1970). They cannot come into equipartition with lighter stars (Spitzer, 1969; Saslaw and De Young, 1971), and so the massive stars sink to the center. There they coalesce one with another and accelerate the building of even more massive stars. Both the limiting mass that can be reached by this process, and the number of supermassive objects which ultimately result are important problems requiring further calculations.

2.2. Evolution

If a hot, thermally supported, supermassive star forms, there are four possible ways it may evolve (Appenzeller and Fricke, 1972; Fricke, 1973, 1974). A non-rotating star with $M \lesssim 4 \times 10^5\ M_{\odot}$ settles down into thermonuclear equilibrium for $\sim 10^5$–10^6 yr. But if $M \gtrsim 4 \times 10^5\ M_{\odot}$, it can explode or collapse into a black hole. Explosion occurs, for a given mass, if the initial heavy element abundance is great enough to produce rapid thermonuclear burning. For example, if $M = 10^6\ M_{\odot}$, explosion occurs if $Z > 0.04$. When Z is too small for a given M, or M is too great for a given Z, thermonuclear energy cannot halt the gravitational collapse. The fourth possibility is that relaxation oscillations occur in which the radius, luminosity, and rate of energy production change periodically in the pulsating star. But this does not seem to occur unless the rate of burning is arbitrarily damped during the explosive phase. The explosive energy of rotating supermassive stars (10^{56}–10^{60} erg) may be several orders of magnitude greater than that of non-rotating ones since rotation stabilizes the star against post-Newtonian instability and increases the upper mass limit for explosions (as against collapse). These explosions may provide an explanation for the optical filaments of NGC 1275, and also for some of the core-halo radio sources.

If the supermassive object which forms is not kept from collapse by gas and radiation pressure, it may be supported mainly by rotation or magnetic fields. No support, however, can last indefinitely, since the disk must eventually cool, and become so thin that it collapses or fragments. The time taken for it to reach this stage depends on details of models, but is usually between 10^5–10^7 yr. When the unstable stage is reached, further collapse and fragmentation occur on a dynamical time scale, which may be only minutes or hours.

The most stable compact supermassive object is a black hole, and often this may be the end result of evolution. However, it is unlikely that all the material goes into the black hole when it first forms; probably much remains behind to form a gaseous disk – or a system of satellites if there is multiple fragmentation – around the black hole. After some initial rearrangements in which gas and fragments close to the hole are swallowed up, and material far away is lost from the system, the total mass surrounding the hole becomes less than the mass of the hole itself. Such a system may be stable for long periods. If it is mostly gas, it evolves on a viscous time scale, during which it is a powerful source of radiation (e.g. Lynden-Bell, 1969). If the fragments have become stars, white dwarfs, neutron stars, small spinars, or small black holes, the system may be stable indefinitely – like our solar system – until secular instabilities destroy the orbits. In this case there may also be strong radiation, especially if the satellites have high magnetic fields. Considerable work has been done on black holes surrounded by accretion disks (e.g. Pringle *et al.*, 1973) but very little is understood about black hole satellite systems. Some of their radiation properties will probably resemble those of multi-pulsar systems (Arons *et al.*, 1974, to be published).

3. Dynamical Interactions between Compact Supermassive Objects and Galactic Nuclei

A compact supermassive object can interact with a galactic nucleus gravitationally and through the effects of its radiation on the surrounding gas. The second interaction is important for models of quasars, Seyfert galaxies, and hydrodynamic explosions in some galaxies. Since the radiation effects have been discussed many times before, and since this symposium is primarily concerned with gravitational dynamics, I'll mostly review the gravitational interactions here.

A dense stellar system loaded with a supermassive object sitting in its middle naturally has a different distribution of stars from an unloaded system. Wolfe and Burbidge (1970) investigated this from the point of view of putting upper limits on the mass of the compact object, by requiring any modification of the stellar density distribution to be consistent with the presently observed projected light and velocity distributions in galactic nuclei. This gave $M_{\text{object}} \lesssim 10^{10}\ M_\odot$ from the velocity dispersion, independent of whether the stellar distribution is relaxed. To determine the structure of the system near the massive object, Wolfe and Burbidge assume that the stellar distribution is in isothermal equilibrium, and they superimpose the gravitational potential of the central mass on the potential of a standard *non-singular* isothermal sphere. Although this procedure indicates the main results, it is not quite consistent since one really wants the solution for an isothermal sphere with a singularity at its center. Subsequently, Peebles (1972) assumed that the star distribution function depends only on a single power of the total energy and considered only the region where the massive object dominated the gravitational field. For a steady state distribution this implies that near the compact object $\varrho \sim r^{-9/4}$, in contrast with the density run $\varrho \sim r^{-2}$ in the outer region of an isothermal sphere. This difference is too small to be detected with present observations unless the M/L ratio of the stars also varies strongly with distance from the center.

Recently J. M. Huntley and I (1975) have looked at the effect of a central massive object on distributions of stars satisfying general polytropic or isothermal equations of state, including the gravity of both the stars and the object consistently. The main results are that these loaded polytropes have a steep central cusp in their density distributions, followed at larger radii by a density plateau where the self gravity of the stars becomes comparable to the gravity of the massive object, and then by a further drop at radii where the gravity of the stars dominate and the density approaches that of a normal polytrope. This structure of a central cusp, plateau, and smooth decrease is in contrast to normal polytropes whose density has zero gradient at the center and decreases smoothly to zero further out. One important effect of the central cusp is to decrease the time scale for stars in the core of the nucleus to collide bodily, compared with the average time scale for this in the rest of the system, or in a system with the same number (and mass) of stars, but without a central object. The dynamical relaxation times of stars in the cusp is also strongly modified by the object. Moreover stars venturing too near the center will be consumed by the massive object, whether it is a black hole or a spinar of some sort.

The general conclusion is that the presence of a single massive object will produce more violent activity in a more concentrated region of the center of the nucleus, than if the object were absent. These modifications have yet to be developed in detail. One especially important problem is to work out the rate at which stars flow into the cusp to replace those which collide or are consumed. All the studies so far have assumed an isotopic distribution function, which is probably adequate for understanding the overall structure of the system, but insufficient for explaining the evolution in the center.

Processes of fragmentation or stellar coalescence which create one massive object, may well produce many. We are then faced with the question of how these massive objects interact dynamically with each other, as well as with the rest of the stars. The simplest problem, of course, is to consider the massive objects as point particles exerting Newtonian forces on each other. The orbits of two massive objects interacting in this way are stable, but three or more are usually unstable.

If three massive objects come close together at the center of the nucleus, two of them can give so much kinetic energy to the third that it escapes. The two then form a more compact binary, to conserve total energy. Momentum conservation requires the binary to recoil in the opposite direction. The time scale for this to happen can be very short, ranging from one dynamical crossing time of the initial binary for the case of a flyby on a direct orbit, to (typically) several hundred or (rarely) thousand crossing times for a three body system with all objects initially given random positions.

To understand this problem, Saslaw *et al.* (1974) have numerically computed the orbits of 25000 triple systems and 250 two-binary systems chosen to illustrate a very wide range of initial orbital conditions. In effect, these scattering experiments turn the computer into a high energy accelerator with particles of $\sim 10^{60}$ GeV, in the usual units. The results yield distribution functions for properties of final orbits as a function of the distributions of initial parameters.

All these numerical experiments give a great deal of information about the general three-body problem, which is interesting quite apart from its applications (Valtonen, 1974). Here however, I'll just mention briefly some of the aspects of the gravitational slingshot relevant to the observational problems raised in the first section.

First, the disruption of three bodies with negative total energy always results in a two sided configuration with respect to the center of mass. This effect of momentum conservation results in two components exactly aligned with the central galaxy if both escape and they are not influenced by the galaxy. Thus the alignment of hot spots in Cygnus A is easily accounted for. In order for them to be approximately equal distances from the central galaxy, they must have nearly equal masses, and their initial orbits must satisfy special conditions which Valtonen will describe later in this Symposium. The small amount of misalignment observed in many radio doubles is likely to come from exchange of angular momentum as the asymmetric galaxy perturbs the orbits of massive objects moving through it at different speeds (Saslaw, 1975).

Next, if we consider the finite extent of the massive object, then it must be compact in order to be accelerated to high enough velocity to leave the galaxy ($\gtrsim 0.01\ c$). As a rough rule of thumb, a finite thumb cannot be gravitationally accelerated to a velocity greater than the escape velocity from its surface without being tidally disrupted. Thus $R \lesssim 10^4\ R_{\text{Schwarzschild}}$ which for $10^8\ M_\odot$ is 0.1 pc, and the radio sources will contain compact components (unless they all become unstable and explode). In fact the typical velocity spectrum from the experiments is fairly broad with a low energy cut off and a long high energy tail. However the velocity of ejection must be $\lesssim 10^4$ km s^{-1}, so that gravitational radiation does not destroy the system. There is indeed some evidence (Mackay, 1973) that the velocities of typical radio sources are of this order.

The numerical experiments show that the particles tend to be ejected fairly close to the plane of the total angular momentum, typically within 30°. If we make the fairly natural assumption that this is also approximately the plane of the galaxy's total angular momentum, then we expect most of the ejections to be nearer the plane of the galaxy than the pole, as found observationally. Of course there will always be the occasional exception and, since this is a statistical effect, one can't learn much from one particular observation.

As the massive object moves out through the galaxy, its orbit is altered by interacting both with the mean field of the galaxy and with the fluctuations in this field which the object itself induces as it passes. The deflection produced by the mean field of a static asymmetric galaxy is straightforward to calculate numerically, and Valtonen (1974) has done this for a Schmidt model potential. It is significant if $V_{\text{escape}} < V_0 \lesssim 1.2\ V_{\text{escape}}$ where V_0 is the initial ejection velocity of the object and V_{escape} is defined as the velocity necessary to reach 100 kpc starting at the center.

The deflection produced by self-induced time dependent fluctuations can be examined analytically for idealized conditions (Saslaw, 1975). The root mean square angle of deflection varies as $(V_{\text{random}}/V_{\text{object}})^3$ in this case, showing a strong velocity dependence. Again if $M_{\text{object}} \gtrsim 0.1\ M_{\text{nucleus}}$ and $V_{\text{object}} \lesssim 1.2\ V_{\text{random}}$ this can also produce a few degrees of misalignment. One prediction of these deflection mechanisms is that the radio sources whose components have the highest ejection velocities should be best aligned. Statistically the largest sources should have some combination of highest velocities and longest lifetimes, but it is not clear how to separate these properties. In this respect it may be significant that the double components of the largest known radio source 3C 236 with a separation 5.7 Mpc are aligned to within 0.5°, and that the components of other large double sources such as DA 240 (2 Mpc), and Cen A (1.57 Mpc) are also among the best aligned.

If a massive object does not quite have enough velocity to escape from a galaxy it will oscillate back and forth through the center on a dynamical time scale until it is damped. The damping produces disturbances in stellar orbits and gas and the differential rotation of the galaxy shears these disturbances. The result might be a peculiar spiral pattern. As far as I know, the detailed structure produced in this way has not been explored. Since many observers give the impression that galaxies contain more peculiar spiral arms than normal smooth ones, it seems an interesting problem.

In addition to its dynamical interactions, a moving massive object will affect the gas in and around the galaxy as it passes (Saslaw and De Young, 1972). Inside the galaxy, if the object is hot and radiates strongly in the ultraviolet, it will form a large H II region. The effects of the ionization front and increased gas pressure may catalyze star formation in nearby clouds close to instability, leaving a luminous trail of bright young stars or H II regions. The trail may also be heated by high energy particles emitted from the massive object. If the massive object is a black hole surrounded by an accretion disk, the type of radiation it emits will depend strongly on the viscosity and magnetic field in the disk. If the viscosity is low, not much gas will fall into the hole and, for no magnetic field, the radiation will be mainly optical. A high viscosity would enable the object to radiate approximately at its Eddington limit – where radiation pressure prevents further gas from falling into the hole – which is $L \simeq 10^{38}\ M/M_{\odot}$ erg s^{-1}. Low frequency radio emission could be produced either by rotating magnetic satellites of the black hole, or by magnetic flares in the rotating gaseous disk. This radiation would evacuate a cavity in the intergalactic gas surrounding the galaxy. A number of mechanisms exist in this situation for accelerating particles relativistically and producing radio synchrotron radiation, and the results could well resemble the observed radio structure of extended sources. However, details of this complex situation have not yet been worked out. It will probably be especially important to take into account the inhomogeneity of the surrounding gas (cf. Rees and Saslaw, 1975).

All these observations, calculations, and speculations that I've tried to describe here, suggest that we may be starting to uncover a new set of ideas which relate the formation and evolution of massive objects in galactic nuclei to a wide range of astronomical problems. However, although there are some exciting trends of evidence favoring the existence of massive objects, I think we should still be cautious about believing in them too strongly. In this respect (and perhaps in some others) it is probably good to recall Hilaire Belloc's whimsical verse.

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DISCUSSION

Lecar: Why, if the ejected components for, say, massive ellipticals, are black holes: is the primary radiation radio, rather than X-ray?

Saslaw: In the case of a black hole surrounded by a disk of gas, the spectrum of emitted radiation will depend strongly on the form and amount of turbulence in the gas and the magnetic field. The result will be a combination of thermal radiation, bremsstrahlung, synchrotron, and Compton scattering with possible important interactions between photons and plasmons. All this is so complicated, however, that no one has worked out realistic detailed spectra yet. It would be especially interesting to know if the massive object starts optically bright when young – and close to its parent galaxy as Lacertids may be – but becomes optically fainter as it ages and radio emission predominates. If the black hole is surrounded by a satellite system of pulsars, then there is no necessity for any optical radiation since we observe old pulsars only in the radio. When young, these systems might also produce optical and X-ray emission.

Bardeen: The thermal radiation from an accretion disk around a supermassive black hole would be in the ultraviolet rather than the X-ray region of the spectrum, since the area of the emitting region increases faster than the maximum luminosity with mass of the black hole.

King: You have indicated that a massive object at the center of a galaxy would produce a central spike of density. Could you indicate quantitatively what should be observed, so that perhaps it can be looked for observationally?

Saslaw: For galactic nuclei with total masses less than about 10^{10} $M_\odot$ in which the mass of the object is $\lesssim 0.1$ of the mass of the nucleus, the central cusp would have an angular diameter much less than one arcsecond. This would put it well within the atmospheric seeing disk, so it would be necessary for high resolution optical observations to be made from above the atmosphere. In the near future, it seems more likely that radio interferometry will be able to measure activity in the cusp.