1 Galaxies, normal and otherwise

To start, let's recall the large-scale structure of galaxies. We are going to focus on bright galaxies, spirals and ellipticals. A lot is known about these objects; in addition to being pretty, they are bright and extended, thus easy to study. We should remember, however, that most galaxies in the universe are neither S nor E. By counting galaxies we can determine the *luminosity function*, that is the number of galaxies at luminosity L (per volume usually). This is called the *Schechter function*, and has the approximate form,

$$\Phi(L) = \Phi_o \left(\frac{L}{L_*}\right)^{-\alpha} e^{-L/L_*} \tag{1.1}$$

Here, Φ_o is a normalizing constant (which depends on the local environment: for instance Φ_o is much larger for a rich cluster than for the field). The slope $\alpha \sim 1.25$; and $L_* \sim 7 \times 10^{10} L_\odot$ is comparable to the characteristic luminosity of bright galaxies (values quoted by Elmegreen, for the V band). We know that the galaxy luminosity connects directly to the galaxy's mass: $M/L \sim 30 - 100$ (in solar units; depending somewhat on the galaxy type, and with some scatter). Thus the Schecter function also measures the mass distribution of galaxies.

Important point: this is a composite luminosity function, determined by adding all galaxy types. Most S and E galaxies sit within a factor of a few of L_*. But the LF has been measured over a range ~ 10 magnitudes, that is a factor $\sim 10^4$ in luminosity, and it keeps rising to smaller luminosities. It follows that *most of the galaxies in the universe are neither spirals nor ellipticals*. Most galaxies are either *Irregulars* (small, patchy structure, rotation supported) or *dwarf Ellipticals* (small, featureless, probably not rotation supported). Check Figure 23.34 of Carroll & Ostlie for a recent break-down of the total LF by galaxy type. In this course we will focus on the big galaxies, which are better understood; but don't forget the little guys.

1.1 Normal galaxies: spirals

Our galaxy is a medium-size spiral, and we can use it to study a "typical" spiral. As with all spirals, its most notable feature is its disk, which contains both stars and gas. The surface mass density of the stellar disk is exponential, $\Sigma(R) \propto e^{-R/H}$, with $H \sim$ few kpc (that number is typical of other nearby spirals). Thus the density of stars dies after several H distances. The gas (HI and molecular gas), however, extends much further; in big spirals gas can be traced to 40-50 kpc, and it has been traced to at least ~ 20 kpc in our galaxy. The surface density of the gas falls, in some galaxies exponentially and in others more irregularly; its radial scale length is generally larger than that of the stars.

What is the structure of the gravitating matter?

The disk is supported vertically by the random motions ("heat") of the stars and gas. Think about individual stars: each one moves up and down, through the galactic plane, in approximate harmonic motion. The vertical extent of its motion depends on the local gravity. Or, think about the stars as a "gas",[1] with random motions at speed σ. We can describe the ensemble of stars in a given volume by a "pressure" ($p \leftrightarrow nm\sigma^2 = \rho\sigma^2$, for number density n and stellar mass m). We then expect the vertical disk structure to be described by hydrostatic equilibrium. This last can be written as a vector equation, or alternatively we can isolate its z ("vertical") component:

$$\nabla p = \rho \mathbf{g} \; ; \qquad \frac{dp}{dz} = \rho g_z \tag{1.2}$$

The typical scale height of the disk, locally, is $H \sim 200 - 300$ pc (varying somewhat for different types of stars, or different phases of the ISM). The surface mass density in the disk can be found in two ways. One, we can measure the local density of stars and gas directly, to get a density of *luminous mass*. Two, we can use the vertical support condition (1.2) to find the local gravity, and from this (remembering Poisson's law for gravity, $\nabla^2\Phi_G = -\nabla \cdot \mathbf{g} = 4\pi G\rho$), we can find the density of *gravitating mass*. This latter approach gives $\Sigma \sim 75 M_\odot/\mathrm{pc}^2$, while the former (counting stars) gives a value that is only about half of this. Thus, about half of the gravitating mass in the local disk is *dark*: it does not emit any radiation that we have been able to detect.

In addition, the galaxy has more dark matter on larger scales. Consider our galaxy: the disk is supported "horizontally" by its rotation; our local rotation speed ~ 220 km/s, which gives a rotation period at the sun's distance (8.5 kpc) of ~ 230 Myr. The stellar orbits are nearly circular, and the galaxy is close to axisymmetric (or truly, we are assuming its mass distribution is spherically symmetric!), so we can use the simplest form of Kepler's law:

$$v_{rot}^2 = \frac{GM(r)}{r} \tag{1.3}$$

[1] If you don't like this idea, look at §1.4 for some discussion.

where $M(r)$ is the mass within r. This provides a simple way to estimate the *gravitating* mass of the galaxy.

Turning to nearby external spiral galaxies, we can use the rotation curve to find the gravitating mass. Rotation curves in big spirals can be traced out to several tens of kpc using HI, and their rotation velocity v_{rot} stays constant out that far. Thus, the gravitating mass $M(< r) \propto r$: the mass of the galaxy keeps rising as we go to larger distances. This is *not* what happens to the total luminous mass (in stars plus gas), however: the integral of an exponential converges to a finite value. Thus, the ratio of total mass to luminous mass increases as we go to larger scales. By the outer $\sim 40 - 50$ kpc in big systems, the ratio of (gravitating mass)/(luminous mass) $\sim O(10)$; there is something like ten times more mass in the system than we can see.

A note on spiral arms...they are of course the most striking, defining features of spiral galaxies. They are not, however, fundametal to the galaxy's structure. Rather they are *waves* or *perturbations* in the self-gravitating disk of the galaxy. Some authors like to work with *linear* density waves – *i.e.* small-amplitude waves with a spiral shape. Other authors like to work with *global* perturbations of the galactic disk – which have a generally spiral shape but need not be linear. Still other authors consider local perturbations – in which a local overdensity, say, is enhanced (due to its own self-gravity) and sheared into a spiral fragment (due to the differential rotation of the disk). Probably each approach describes some fraction of spiral galaxies.

And a note on the dark matter ... we have no direct observation of the spatial distribution of the dark matter. It seems likely, however, that the dark haloes of spiral galaxies are spheroidal – *i.e.* supported by their internal, random motions ("heat"), just as elliptical galaxies are (as we discuss in the next section). This idea comes from numerical simulations of structure formation, as well as the fact that the dark matter (by assumption!) does not "cool", so can't dissipate its internal energy – thus it probably has not been able to flatten into a disk.

1.2 Normal galaxies: ellipticals

Elliptical galaxies are quite different. They are smooth and featureless structures, showing a core (of roughly constant density) and an outer envelope (or declining density). Their surface brightness follows the heuristic De Vaucoulers law: $\Sigma(r) = \Sigma_o e^{-(r/r_o)^{1/4}}$ (where r_o is a constant, a length scale). In a three-dimensional system such as this, the surface brightness is a projection of the underlying 3D spatial density:

$$\Sigma(R) = 2\int_R^\infty n(r)\frac{rdr}{\sqrt{r^2 - R^2}} \qquad (1.4)$$

The stellar density is decently well fit by $n(r) = n_o/[r(r + a)^2]$, or by similar (analytic) forms which have a characteristic "core" radius, $a \sim 1 - 2$ kpc. [2]

We might think they are very simple...but that's not the case. One hint comes from rotation: elliptical galaxies are not rotation supported. In a large elliptical the rotation speed is much smaller than the dispersion: $v_{rot} \lesssim 0.1\sigma$ typically. (For smaller galaxies, v_{rot} is a larger fraction of σ). In addition, E galaxies are truly *three-dimensional*. To see this, consider shape of the surface brightness isophotes. They are, of course, elliptical (and close to circular in some E galaxies). But, the direction of their major axis *rotates* going out from the galactic center. This *isophote twist* is a clear sign of a trixial system. Both of these facts tell us that the stellar orbits must be complex, randomly oriented, and not necessarily closed (that is a star can wander through much of the volume of the galaxy over it's lifetime).

Despite the complexity of the orbits, we can find a simple model of the structure of the galaxy. Assume spherical symmetry to simplify, and following the arguments above write down a "hydrostatic balance" equation for the stars:

$$\frac{d(\rho\sigma^2)}{dr} = \rho\frac{GM(r)}{r^2}\ ; \qquad \frac{dM}{dr} = 4\pi\rho r^2 \qquad (1.5)$$

Now do some algebra, and combine these into one second-order ODE for $\rho(r)$. The resulting equation has two solutions. One is analytic, $\rho \propto 1/r^2$. This solution diverges in the center (that's not good) and its mass, $M(r) \propto \int \rho r^2 dr$, diverges at infinity (that's also not good). The other must be found numerically, but turns out to have a finite central density, and a characteristic *core radius*; at large radii it approaches the first, analytic, solution. And: you have no doubt recognized this solution, from last term. It is the *self-gravitating isothermal sphere*, an important solution in several different astrophysical applications.

[2] This is the "NFW" (Navarro, Frenk & White) profile; it turns up commonly in numerical, N-body simulations of collapsing, self-gravitating galaxies; and is a reasonable match to the profiles of real galaxies.

The divergence at infinity cannot be fixed analytically in this approach. The most attractive solution that I know of, comes from considering the internal velocity distribution of the stars; those at the highest velocities will exceed the escape velocity of the galaxy. King took this into account in numerical models of the isothermal sphere, and found solutions which are nicely well-behaved at infinity. He also gives an *approximate* expression for the density of the resulting system:

$$\rho_{King}(r) = \frac{\rho_o a^3}{(r^2 + a^2)^{3/2}} \qquad (1.6)$$

What about the mass of an elliptical? Is dark matter important? Due to the complexity and variety of the shapes of allowed stellar orbits, we can't easily use Kepler-type arguments, as we could for spirals. We can of course use approximate arguments, such as the virial theorem, to estimate M_{grav} from the stellar velocity dispersion: $GM_{grav} \simeq \sigma^2 r$. Quantitatively, however, to get accuracies at the tens of percent level is not as easy as it is for spirals. Several approaches can be used:

• One, the strongest result in my opinion, uses the small (but non-trivial) minority of the population which have flattened, extended HI disks. These disks rotate, in simple Keplerian motion, which allows us to find the gravitating mass directly. The result: M/L for big E's is similar to that for big S's, ($\sim 10 - 30$ typically), and also tends to increase with radius.

• Another approach uses the hot, X-ray loud gas found in every big elliptical. This gas sits in approximate hydrostatic equilibrium in the potential well of the galaxy; from its spatial distribution we can estimate the gravitating mass. I defer details here until the next chapter; the results for M/L are generally consistent with those from flattened HI disks.

• Careful interpretation of the stellar kinematics involves making a model of the gravitational potential, doing numerical integrations to find out what the allowed stellar orbits look like, and verifying that if one populated those orbits with stars the resulting object would look like a real galaxy and would reproduce the potential assumed at the beginning. At present it is not very common to be able to do this in the far outer regions of elliptical galaxies. In the inner, bright portions of the galaxy the mass is dominated by stars rather than by dark matter.

1.3 Query: why are they different?

Although this isn't a course in galactic structure, it seems appropriate to ask why there are two characteristic types of big galaxies – one flat and supported by rotation, the other round and supported by random motions. Two possibilities have been discussed for ages:

• We might think that galaxies form in isolation: by gravitational collapse of their dark matter, and subsequent dissipational collapse of the baryonic gas (normal ISM!) within the dark halo. (An important point here is that normal, baryonic material can radiate away its interal energy; so it can cool, and collapse in a gravitational field. Dark matter, being non-baryonic, cannot). If this is the case, then the E/S difference might be due to how early in the process stars formed. Early star formation might lead to an E; later star formation, after the ISM has collapsed into a disk, could lead to an S.

• However there's another possibility: galaxies might influence each other during their formation process. Two facts are germane here. First, we know that E's are commonly found in regions of high galaxy density – rich clusters of galaxies. Second, simulations show that if two spiral galaxies collide, closely enough for their stars to remain bound, the energy of the collision will heat the stars and "puff up" the galaxy – *i.e.* making something that looks like an elliptical. So .... it may well be that E's are more common in clusters, because conditions (at least early on) were right for protogalaxy-protogalaxy collisions.

Which of these is right? I suspect the answer lies somewhere inbetween – this is still an active area of current research.

1.4 Interlude: stellar dynamics

How can we justify talking of a stellar "pressure"? Here's a quick overview of the argument, following Binney & Tremaine. Consider a distribution function of stellar velocities, $f(\mathbf{x}, \mathbf{v})$ (the number of stars "at $\mathbf{x}$ and $\mathbf{v}$"). If stars are conserved, and there are no collisions (in which the position and/or the velocity of the star changes instantaneously, by a finite amount), then the evolution of f is goverened by the motion of individual stars through $(\mathbf{x}, \mathbf{v})$ phase space:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f + \mathbf{a} \cdot \nabla_{\mathbf{v}} f = 0 \qquad (1.7)$$

(Think: does this make sense? We're just counting stars). Here, $\nabla_{\mathbf{x}}$ is the usual spatial gradient, $\nabla_{\mathbf{v}}$ is the gradient in phase space with respect to the velocity coordinates, $\mathbf{v}$ is the velocity and $\mathbf{a} \equiv d\mathbf{v}/dt$ is the acceleration. Here, we specify $\mathbf{a} = \mathbf{g} = -\nabla\Phi_g$, *i.e.* the gravitational acceleration. Now, we can derive a couple of useful results.

First, integrate (1.7) over all velocities. We get (specify to Cartesian coordinates to make the algebra more transparent):

$$\int \frac{\partial f}{\partial t} d^3\mathbf{v} + \int v_i \frac{\partial f}{\partial x_i} d^3\mathbf{v} + g_i \int \frac{\partial f}{\partial v_i} d^3\mathbf{v} = 0 \quad (1.8)$$

But now, the last term goes to zero (why? The i component of the integrand becomes $(\partial f/\partial v_i)dv_i$, a perfect differential; it integrates to zero if f has "reasonable" boundary conditions). Also, in the second term we can take the d/dx_i outside the integral (remember that $\mathbf{x}$ and $\mathbf{v}$ are independent coordinates). We can define the stellar density and mean velocity by

$$n = \int f d^3\mathbf{v}\,; \qquad \langle\mathbf{v}\rangle = \frac{1}{n}\int f\mathbf{v} d^3\mathbf{v} \qquad (1.9)$$

Finally, (1.8) becomes

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x_i}\left(n\langle v_i\rangle\right) = \frac{\partial n}{\partial t} + \nabla\cdot\left(n\langle\mathbf{v}\rangle\right) = 0 \quad (1.10)$$

(here and after I'm using ∇ to mean the usual $\nabla_{\mathbf{x}}$). But this is simple: it is just the continuity equation for stars.

Now, multiply (1.7) by $\mathbf{v}$ before integrating over velocity space. The algebra is longer, but the approach (and mathematical tricks) are the same. One version of the result is

$$n\frac{\partial\langle v_j\rangle}{\partial t} - \langle v_j\rangle\frac{\partial}{\partial x_i}\left(n\langle v_i\rangle\right) + \frac{\partial}{\partial x_i}\left(n\langle v_i v_j\rangle\right) = n g_j \quad (1.11)$$

Now, velocity $\mathbf{v}$ is partly due to streaming (all stars share the same mean velocity) and partly due to random motions about this mean. Thus, the mean value $\langle v_i v_j\rangle$ can be split into a part that describes the streaming motion ($\langle v_i\rangle\langle v_j\rangle$) and a part that describes the internal velocity dispersion,

$$\sigma_{ij}^2 = \langle v_i v_j\rangle - \langle v_i\rangle\langle v_j\rangle \qquad (1.12)$$

Using this, and letting $\mathbf{v}$ now represent the *mean* streaming velocity, we can write (1.11) as

$$n\frac{\partial\langle v_j\rangle}{\partial t} + n\langle v_i\rangle\frac{\partial\langle v_j\rangle}{\partial x_i} = n g_i - \frac{\partial}{\partial x_i}\left(n\sigma_{ij}^2\right) \quad (1.13)$$

or – if we note that $nm\sigma_{ij}^2$ is equivalent to a pressure, p – this becomes

$$n\frac{\partial\mathbf{v}}{\partial t} + n\mathbf{v}\cdot\nabla\mathbf{v} = n\mathbf{g} - \frac{1}{m}\nabla p \qquad (1.14)$$

This is the general dynamical equation for collisionless stellar systems. In a steady state, with no bulk flows, this reduces to the usual hydrostatic equilibrium: $\nabla p = \rho\mathbf{g}$ (being slightly cavalier about the pressure, which is OK for our purposes here).

1.5 The not-so-normal ones: active galaxies

About one per cent of the bright galaxy population is "active". That is, they contain small, highly energetic, *non-stellar* events in their nuclei. (The fraction is less common in smaller galaxies; and more common in bright galaxies at high redshift). Some active galaxies are found optically, others are found in radio. We will return to this topic later in the course. For now, here, I just note the classes and general properties, with an eye to their historical discovery.

Seyfert galaxies are spirals with very bright nuclei. These nuclei are most easily detected by their strong, optical emission lines; they also have nonthermal continuum emission. They also have small ($\lesssim$ kpc), faint radio sources in their cores. The most important point here is that this phenomenon cannot be explained simply by stars: some non-stellar event is taking place in these nuclei.

Radio galaxies are ellipticals which have double-lobed radio sources, fed by jets emanating from galactic core. They also have compact, non-stellar nuclei, but on the weak side compared to bright Seyferts.

Quasars were originally called "quasi-stellar objects". They are bright, compact (inferred from from variability), have very strong emission lines (this is how they were first found), and a strong nonthermal continuum. Some (maybe 10%) are "radio-strong", with a radio-loud core and extended double-lobed radio structure. Some of these ("blazars"; maybe 10% again?) are violently variable, showing a large $\Delta L/L$ on short time scales. These generally also contain radio jets with superluminal motion. Initially no galaxy could be seen around these very bright, small sources – hence the name QSO. With dedication and better technology we now can image the underlying galaxies. This area is still under discussion, but it looks as if quasars show the same host-galaxy split as to Seyferts and AGN:

radio-loud from E's and radio-weak from S's. We now have found quasars out to $z \sim 5$, and probably higher by the time you read these notes.

What all of these objects have in common is an *Active Galactic Nucleus (AGN)*. An AGN is characterized by a high luminosity (which can be comparable to the luminosity of the entire host galaxy); a small intrinsic size (inferred from variability: $\lesssim$ light-day or light-month); a non-stellar spectrum (that is, from diffuse gas, often including nonthermal particles and B field); and a preferred axis (as shown by radio jets – showing us net angular momentum of the core?). The general model is accretion of matter onto massive black hole in the nucleus of the galaxy.

1.6 The beast in the core

A striking recent result is that every galaxy appears to have a massive dark object in its core. At this point we have no definite proof that these massive things are black holes; that would require resolving the event horizon and finding some definitive signature, for instance emission lines red/blue shifted due to the orbital speed of gas in the last stable orbit. What we can do, however, is use gravity to detect a massive dark object (MDO): that is, a total gravitating mass much larger than what can be accounted for by stars in the region.

1.6.1 Techniques: normal galaxies

There are two important detection techniques here, for galaxies without strong AGN. In what follows I use the term "bulges" to mean either elliptical galaxies, or the bulges of early-type spirals.

•**gas disks** Some bulges contain gas disks in (apparent) Kepler rotation around a central MDO. A small number of these, such as M87, have been resolved fairly close to the MDO. A few other galaxies have inner gas disks with maser spots which are easy to resolve with the VLBA and which can also give the gas velocities. A larger number of galaxies have gas disks which can be resolved with HST (albeit not so close to the MDO). Emission line velocities from these disks, again assuming Keplerian rotation, can be used to find the central mass.

•**stellar cusps** Most E's and spiral bulges, however, do not have nice gas disks in their cores. For these, we need to use the fact that a central point mass affects the distribution of nearby stars. A central star cluster with no MDO is well described by a self-gravitating isothermal sphere – which you remember from earlier in the course. The stellar density is (approximately) constant in the inner region of the cluster. On the other hand, if a large point mass, M_{BH}, sits at the center, it will cause the stars to form a *density cusp*, of characteristic scale $r_{cusp} \sim GM_{bh}/\sigma^2$ (if σ is the random stellar velocity).

• **Results** The results of this work is striking: *essentially every bulge yet observed (carefully enough) contains a massive black hole*. Furthermore, the mass of the central object correlates tightly with σ, the velocity dispersion of the nearby stars. This is called the $M_{bh} - \sigma$ relation, usually quoted as

$$M_{bh} \sim 1 \times 10^8 \left(\frac{\sigma}{200 \text{ km/s}} \right)^x M_\odot.$$

The exact value of the exponent is still being argued about: Kormendy (2001) gives $x = 3.65$, while Merritt & Ferrarese (2001) give $x = 4.80$. I'd take $x \sim 4$ as a reasonable guess for now. About 40 galaxies had been studied as of 2001 – about 2/3 of them by stellar cusps, 1/3 by gas disks – with BH masses extending from a few million to a few billion solar masses. [3]

1.6.2 Techniques: extend to AGN

The techniques just listed don't work for most AGN, due to the very bright nonstellar nucleus which swamps the non-AGN signal. Two other techniques are being developed. I personally don't yet find them as convincing as gas disks and stellar cusps, but they have their adherents and the techniques are becoming more reliable as time passes. They are:

• **Reverberation mapping**. Go back to our cartoon of the emission line clouds close to the AGN. The line widths tell us the velocity of the gas, which we assume is gravitationally bound to the BH. To get its distance, we look at variability. The gas emitting the broad lines is photoionized by the central engine; when the ionizing flux varies, so will the ionization level in the line-emitting gas, *but after a delay due to the light travel time*. Monitoring of both the (ionizing) continuum and

[3] Comment from the author: *this is very striking*, and was totally unexpected. Just about everyone in the field thought that only AGN would have a massive BH in the core. A minor complication was that quasars are much more common at high redshift – as discussed below – so people were aware that there must be some ex-quasars nearby. But few people suspected, before a few years ago, that MDO's would be so very common.

the emission lines can give us the distance of the line-emitting gas from the BH. Combining this with the linewidth gives us the mass of the BH. This has been done for only a handful of AGN so far; the results (as quoted in Merritt & Farrarese 2001) fit nicely on the $M_{bh} - \sigma$ curve determined for non-active bulges.

• **X-ray line profiles**. This attractive idea is still being pursued observationally. The Kα line of iron has now been seen in Xrays in several objects. The data suggest it is very broad ($\lesssim c/3$ linewidth), and has "an asymmetric red wing consistent with gravitational redshift". This is still a very new technique, and needs careful modelling of the accretion flow in order to do anything quantitative. Such work may be coming.

1.6.3 The galactic center: stellar orbits

The center of our galaxy is a special case, because it's so close (and easier to observe), and of course because it's of great personal interest to us. Different techniques can be used here than in external galaxies, because we can see fainter objects and resolve smaller scales. On the other hand, the GC is heavily obscured as seen from here, so we can't do anything optically. Radio, IR and high frequencies (X- and γ rays) are our tools.

As seen in the radio the region is quite a mess – a complex distribution of thermal gas (HII regions), cold molecular gas, and nonthermal emission (SNR and diffuse). Most of this is extraneous to our focus here, namely the existence and size of an MDO in the GC: we need to search for a compact object and/or ordered gas motions. Both things exist ...

• **Streaming gas** can be detected in radio continuum, and its velocity measured with radio recombination lines. Its structure has been called a "mini-spiral", although it is not as ordered as that name would suggest. Its physical extent $\sim 1 - 22$ pc, and its ordered rotation speed $\sim 100 - 200$ km/s. If this gas is in ordered, Keplerian motion it points to a gravitating mass of a few $\times 10^6 M_\odot$. This was the first strong sign, but the uncertainty of the gas orbits and the lack of strong constraints on nuclear stars (could the mass be just a dense star cluster?) kept the skeptical (like your author) from accepting this as a detection of a BH.

• **Sgr A*** has long been known to be an unresolved radio source at what seems to be the dynamical center of the galaxy. This argument is made as follows. The data verify that Sgr A* is at the dynamical center of the streaming gas ring/spiral, and also at the center of the nuclear star cluster (described next). A more indirect argument is it's lack of random motion. VLB monitoring over 16 years showed that it has only the parallax consistent with our motion around the GC; its own space velocity can be no more than 15 km/s. This is so much lower than other random motions that we can infer it's a massive object moving only very slowly. It is unresolved, even at VLB scales[4], making its physical size smaller than ~ 1 AU. It is a compact, variable synchrotron source: a small version of what we find in other AGN. We don't have the resolution at X- or γ-rays to separate its high-frequency emission from the general mess in the GC region; but an old report of an $e^+ - e^-$ annihiliation line, at 0.5 Mev, from the direction of the GC was tantalizing (and unfortunately has never been repeated).

Thus: there is suggestive evidence of a massive, compact thing in the GC. The recent result that tied this down and convinced the skeptics is IR imaging of the central star cluster. Individual stars can be distinguished easily within the central $\sim$ pc-sized star cluster; and 10 years of monitoring (as reported by Schödel etal, in a 23-author paper) allow measurement of the stars' proper motions. This is a great piece of work: the orbits of individual stars were followed long enough to track them through both peri-center and apo-center passage, which allows a good determination of the orbital parameters *and the mass of the central object*. This data fits well with other recent estimates of the mass of the MDO, such as from velocity dispersions; modelling seems to demonstrate robustly that the gravitating mass must be a point mass rather than a dense, but extended, star cluster. The bottom line: the core of our galaxy contains a MDO, almost certainly a BH, of $M_{bh} \sim 3 \times 10^6 M_\odot$.

References

Much of the general discussion is just "off the top of my head". Some useful general references on galaxies are

• Binney & Merrifield, *Galactic Astronomy*

• Elmegreen, *Galaxies & Galactic Structure*

[4]That really means its angular size is small enough to be affected by interstellar scattering, due to the radio waves propagating through the turbulent ISM

• Sparke & Gallagher, *Galaxies in the Universe*

For more detail than you want on stellar dynamics and the structure of galaxies, a very good book is

• Binney & Tremaine, *Galactic Dynamics*

I'll put up AGN references later in the course. For now, chapter 26 of Carroll & Ostlie is a nice introduction.