Lots of Material!

- Going over the slides there were ~30 slides per lecture and 27 lectures- 800 slides!
- Wide variety of topics:
  - stellar physics
  - dynamics
  - gas physics
  - dust
  - star formation
  - galaxy properties
  - active galaxies ..... stuff not covered in text and the professors insistence on NOT covering stuff the text covers ...argh

Congratulations for hanging in!

FINAL EXAM

Saturday, December 16 1:30pm-3:30pm

- Exam is in this room
- Cumulative, but with emphasis after the midterm
- No notes or books allowed
- Bring calculator
Maybe We Had a Bit of This

Eddington ratio sets the minimum mass for an accreting object
\[ L \sim 10^{44} \text{ ergs/cm}^2/\text{sec} \sim M_{\text{min}} > 10^6 M_\odot \] (most massive Neutron stars \( \sim 2 M_\odot \))

Rapid variability sets a length scale \( R \sim c \delta t \) (\( \sim 1 \text{ hours} \sim 10^{14} \text{ cm} \))

Huge mass inside small radius--- special object, but this is for AGN; what about non-AGN hosting galaxies?

But how can we measure the mass ??

Dynamics
Motion of stars
Motion of gas
'Reverberation' mapping
What do we need to dynamics

Need to examine the velocity field of the tracer at length scales where the mass of the black holes dominates the potential.

In the Milky way this occurs at $\sim 1$-2pc for $M_{BH} \sim 4 \times 10^6 M_\odot$.

For similar MW like galaxies this corresponds to $\sim 0.01$ arc sec at distance of Virgo Clusters.

So 'need' more massive BH in a region with high ratio of black hole to stellar mass. Using E galaxy scaling laws for mass this occurs at

$$\theta_{BH} \sim 0.11'' [M_{BH}/10^8 M_\odot](\sigma/200 \text{km/sec})^{-2}(D/20 \text{Mpc})^{-1}$$

Thus need HST or next generation 30m telescopes with Adaptive optics.

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Discovery of black holes

- First evidence for an object which 'must' be a black hole came from discovery of the X-ray source Cygnus X-1.
  - Binary star system... black hole in orbit around a massive O-star; period =5.6 days - not eclipsing.
  - Mass of x-ray emitting object 7-13 M- too high for a NS. Object emits lots of x-rays little optical light.
  - X-rays produced due to accretion of stellar wind from O-star.
  - 2kpc away.

 Velocity curve of the stellar companion
It is a massive O star.

$$f(M) = P_{\text{orb}} K^3 / 2 \pi G = M_1 \sin^3 i / (1 + q)^2.$$  

$q=M_2/M_1$

The value of the mass function is the absolute minimum mass of the compact star.
The Center of the Milky Way

- The center of the MW is called Sagittarius A* (SgrA*) from the name of the radio source at the dynamical center of the MW.
- This is also the location of a weak, time variable x-ray (log $L_x \sim 34$ - 100x less than a typical x-ray binary) and IR source
- The radio source is very small (VLBI) (<0.0005"<50R$_\odot$ for M=4x10$^6$M$_\odot$ BH at d=8kpc)
- At SgrA* $1''=0.04$pc=1.2x10$^{17}$ cm ,0.5mas=6AU
MW Galactic Center

- galactic centers are 'special' places
- MW galactic center

Motion of Stars Around the Center of the Milky way- see
http://www.youtube.com/watch?v=ZDxFjq-scvU
http://www.mpe.mpg.de/ir/GC/
Two teams led by R. Genzel and A. Ghez have measured the 3-D velocities of individual stars in the galactic center. This allows a determination of the mass within given radii. The inferred density of the central region is $>10^{12} M_{\odot}/pc^3$.

As shown by Genzel et al., the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass $2.6 \times 10^6 M_{\odot}$ and density $20 M_{\odot} pc^{-3}$ or greater cannot be stable for more than about 10 million years.

**Velocity Distribution of Stars Near the Center of the MW**

Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.
Some Problems with Sgr A*

- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ($L/L_{\text{Edd}} \sim 10^{-10}$)
- What happens to the accretion energy- where does the mass and energy go

- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities TODAY! (AGN evolution)
While stars are moving very fast near the center (Sgr A*) the upper limit on its velocity is 15 km/sec. If there is equipartition of momentum between the stars and SgrA* then one expects

\[ M_{\text{SgrA*}} > 1000M_\odot (M_\star / 10M_\odot) (v_\star / 1500\text{km/sec})(v_{\text{sgrA*}} / 15\text{km/sec})^{-1} \]

Where we have assumed that the stars we see have a mass 10M_\odot and a velocity of 1500 km/sec.

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**Schwarzschild and Kerr Metric**

- for a Schwarzschild BH the innermost stable radius is \(3r_g=6GM/c^2\) - there are no stable circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at \(r_+=GM/c^2\) The spinning black hole drags the the inertial frame-
- The smaller critical radius allows more energy to be released by infalling matter
  - For a Kerr BH, 0.423 of the rest mass energy can be released.
What About Other Supermassive Black Holes?

- At the centers of galaxies - much more distant than SgrA*.
- First idea: look for a 'cusp' of stars caused by the presence of the black hole - doesn't work, nature produces a large variety of stellar density profiles... need dynamical data.
- Dynamical data: use the collisionless Boltzmann eq (seen this before).
- $V$ = rotational term; velocity dispersion has 3 components $\sigma_r$, $\sigma_\phi$, $\sigma_\theta$.

\[
M(r) = \frac{V^2_r}{G} + \frac{\sigma^2_r}{G} \left[ - \frac{d \ln \nu}{d \ln r} - \frac{d \ln \sigma^2_r}{d \ln r} - \left( 1 - \frac{\sigma^2_\theta}{\sigma^2_r} \right) - \left( 1 - \frac{\sigma^2_\phi}{\sigma^2_r} \right) \right]
\]

Kormendy and Richstone (2003)

Please fill in your course evaluation!
- 4 people have done so as of this morning.

- [www.CourseEvalUM.umd.edu](http://www.CourseEvalUM.umd.edu)
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc.? - or dull, boring, stodgy, unprepared?
- Your responses are strictly anonymous. I only see the statistics.
- Helps me and future students!
Finding SMBHs

• Detect SMBHs via presence of an AGN (~10% today) OR
• Via dynamics (motion of stars or gas)... imply ~100% at $M_{\text{galaxy}} > 10^{10} M$.  

Example of data for the nearest galaxy M31

• Notice the nasty terms
  • $V_r$ is the rotation velocity $\sigma_r, \sigma_\theta, \sigma_\phi$ are the 3-D components of the velocity dispersion $\nu$ is the density of stars

• All of these variables are 3-D; we observe projected quantities!

• The analysis is done by generating a set of stellar orbits and then minimizing
  • Rotation and random motions (dispersion) are both important.

• Effects of seeing (from the ground) are important smear the image, reduce BH dynamical signal...
Marconi

NGC1277 - Velocity Data and BH Mass

- Top is rotation curve vs. distance from center
- Middle is velocity dispersion vs. distance from center
- Bottom 2 curves are measures of the non-gaussianity of the velocity field (sensitive to distribution of orbits)
- Plate scale is 1 kpc = 13" so for this galaxy effect of BH on orbits is occurring at ~5", can do it from the ground
Measuring the Mass of a SuperMassive Black Hole

- Image of central regions and velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion axis (horizontal) covers a velocity interval of 1445 km s⁻¹, while the spatial axis (vertical) covers the central 3 arcsec;
Measurement of Kinematics of Gas

- Image of optical emission line emitting gas around the central region of the nearby giant galaxy M84

HST STIS Observations of the Nuclear Ionized Gas in the Elliptical Galaxy M84
G. A. Bower, R. F. Green, D.

Analysis of Spectral Data for M84

- Mass of central object $1.5 \times 10^9 \, M_{\odot}$

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>Uncertainty Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black hole mass ($M_\bullet$)</td>
<td>$1.5 \times 10^9$</td>
<td>(0.9-2.6) $\times 10^9$</td>
</tr>
<tr>
<td>Disk inclination (deg)</td>
<td>80</td>
<td>75-85*</td>
</tr>
<tr>
<td>Disk P.A. (deg)</td>
<td>83</td>
<td>80-85</td>
</tr>
<tr>
<td>Gas systemic velocity (km s$^{-1}$)</td>
<td>1125</td>
<td>1100-1150</td>
</tr>
<tr>
<td>Intensity law</td>
<td>$I(r) \propto r^{-1}$</td>
<td>...</td>
</tr>
<tr>
<td>$R(r)$ inner radius (pc)</td>
<td>1</td>
<td>0.3-3</td>
</tr>
<tr>
<td>$V(r)$ inner radius (pc)</td>
<td>0.03</td>
<td>0.01-0.1</td>
</tr>
<tr>
<td>PSF FWHM (arcsec)</td>
<td>0.05</td>
<td>0.04-0.06</td>
</tr>
</tbody>
</table>

* Lower mass requires lower inclination.

Velocity of gas vs distance from center of emission along 3 parallel lines
Centaurus - A

- 2 dimensional velocity maps for gas and stars allow assumptions to be checked (Neumayer et al, Cappelari et al.)

![Gas Velocities](image)

**Figure 4:** Spherical anisotropic Jeans model

\[ M_{BH} = (5.5 \pm 3.0) \times 10^7 M_{\odot} \]

Constraints from stars compared to those from Gas Velocities

![NGC4258](image)
Use of Masers for an AGN

- The nearby galaxy NGC4258 has a thin disk which is traced by water maser emission.
- Given the very high angular and velocity resolution possible with radio observations of masers, the dynamics of the system are very well measured.

Other Masers

Kuo et al 2010
What About AGN in General??

• We believe that the incredible luminosity of AGN comes from accretion onto a black hole.
• However the 'glare' of the black hole makes measuring the dynamics of stars and gas near the black hole very difficult.

• Technique: reverberation mapping (Peterson 2003)
  – The basic idea is that there exists gas which is moderately close to the Black Hole (the so-called broad line region) whose ionization is controlled by the radiation from the black hole.
  – Thus when the central source varies the gas will respond, with a timescale related to how far away it is.

Virial Mass Estimates

\[ M_{BH} = f \, v^2 \, R_{BLR} / G \]

Reverberation Mapping:

• \( R_{BLR} = c \, \tau \)
• \( v_{BLR} \)

Line width in variable spectrum
The Geometry

• Points $(r, \theta)$ in the source map into line-of-sight velocity/time-delay $(\tau)$ space $(V, \tau)$ according to $V = V_{\text{orb}} \sin(\theta)$, where $V_{\text{orb}}$ is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.

• The idea is that the broad line clouds exist in 'quasi-Keplerian' orbits and respond to the variations in the central source. Lower ionization lines are further away from the central source.

• So

$$M_{\text{BH}} = f r V^2 / G$$

$f$ is a parameter related to geometry and the orbits of the gas clouds. Assumption is that gas is in a bound orbit around the BH

A Quick Guide to Photoionized Plasmas

• Fundamental idea photon interacts with ion and electron is ejected and ion charge increased by 1

• $X^+ h\nu \rightarrow X^{+1} + e^-$

• Ionization of the plasma is determined by the balance between photonization and recombination

• Photoionization rate is proportional to the number of ionizing photons x number of ions x the cross section for interaction and the recombination rate to the number of ions x number of electrons x atomic physics rates

• Steady state ionization determined not by temperature, but by balance between photo-ionization ($\sim F_e$ spectrum) and recombination $(n_e)$:

$$n_e \sum F_1 \alpha(T_e) \, dE = n_{e+1} \frac{\alpha(T_e)}{n_e} = n_{e+1} \frac{\alpha(T_e)}{n_e}$$

• Ionization $n_{e+1} / n_e \propto F / n_e \propto L / n_e r^2 \equiv \xi$

$\xi$ is the ionization parameter (also sometimes called $U$)
• A selection of emission lines ranging from high ionization CIV to low ionization Mg II

• Ionization state corresponds to higher values of the ionization parameter
  $\xi \sim L/n_e r^2$

In Other Words

• For each ion:
  – Ionization = recombination
  – $\sim$ photon flux $\sim$ electron density

• For the gas as a whole
  – Heating = cooling
  – $\sim$ photon flux $\sim$ electron density

• => All results depend on the ratio photon flux/gas density or "ionization parameter"

Peterson (1999)
What is Observed??

- The higher ionization lines have a larger width (rotational speed) and respond faster (closer to BH)
- Line is consistent with idea of photoionization, density \( \sim r^{-2} \) and Keplerian motions dominating the line shapes \( (v \sim r^{1/2}) \)
- Such data exist for \( \sim 40 \) sources
- At present \( M_{BH} \) can be estimated to within a factor of a few: \( M \propto \text{FWHM}^2 \text{L}^{0.5} \)

Dotted line corresponds to a mass of \( 6.8 \times 10^7 M_\odot \)
Peterson and Wandel 1999

But What About Objects without a Strong Continuum

- There exists a class of active galaxies (type II) which do not have broad lines and have a weak or absent 'non-stellar' continuum
- Thus there is no velocity or luminosity to measure - rely on 'tertiary' indicators.
- It turns out (very surprisingly) that the velocity dispersion of the stars in the bulge of the galaxy is strongly related to the BH mass
  - This is believe to be due to 'feedback' (more later) the influence of the AGN on the formation of the galaxy and VV
  - The strong connection between the BH and the galaxy means that each know about each other

Velocity dispersion of stars in the bulge
Reverberation Masses and Dynamical Masses

- In general for the same objects mass determined from reverberation and dynamics agree within a factor of 3.
- This is 'great' but
  - dynamical masses very difficult to determine at large distances (need angular resolution)
  - Reverberation masses 'very expensive' in observing time (timescales are weeks-months for the response times)
  - If AGN have more or less similar BLR physics (e.g. form of the density distribution and Keplerian dynamics for the strongest lines) then we can just use the ionization parameter and velocity width (\(\sigma\)) of a line to measure the mass
    \[
    \xi = \frac{L}{n_e r^2}
    \]
    find that \(r \sim L^{1/2}\)
  - Or to make it even simpler just L and \(\sigma\) and normalize the relation (scaling relation)- amazingly this works!

\[
M_{BH} \sim K \sigma^2 L^{1/2}
\]
Where K is a constant (different for different lines which is determined by observations
This is just
\[
M_{BH} = \frac{v^2 R_{BLR}}{G}
\]
with an observable (L) replacing \(R_{BLR}\)

Nature has chosen to make the size of the broad line region proportional to \(L^{1/2}\)
Masses of Distant Quasars - M. Vestergaard

- Using this technique for a very large sample of objects from the Sloan Digital Sky Survey (SDSS)
- Maximum mass $M_{\text{BH}} \sim 10^{10} M_\odot$
- $L_{\text{BOL}} < 10^{48}$ ergs/s

Co-evolution of Galaxies and Black Holes - Summary

- Theoretical models for the coevolution of galaxies and supermassive black holes are based on combining analytic models and numerical simulation of structure formation in the dark matter with ideas about how star formation and black hole accretion operate in practice
- Over cosmic time, galaxies grow through two main mechanisms: accretion of gas and mergers
- In a merger, the disk component of each galaxy is scrambled and tidal forces between the two galaxies drain away angular momentum from the cold gas in the disk of the galaxy, allowing it to flow into the inner region, delivering gas to the supermassive black hole.
- The scrambled disk material settles into a newly created spheroid.
- If the each of the merging galaxies contained their own supermassive black holes, these too might merge to form a single larger one.
- The release of energy from the merger-induced AGN and starburst is so intense that it may blow away most or all of the remaining gas in a powerful outflow.
- The end result is a single galaxy with a larger bulge and a substantially more massive black hole (Heckman and Kauffmann 2012)
Constraints on Rest Mass of Black Holes

- Black holes can grow via two paths
  - accretion
  - merger

- It is thought that, at z>1 that many galaxies (esp. elliptical galaxies) grow through mergers.
  If these galaxies had modest black holes, and if the black holes also merged, one could grow the supermassive black holes that lie in most large galaxies observed today. This process would produce strong gravitational radiation which is the goal of the LISA mission

- Alternatively (or in parallel) we know that BHs are growing via accretion - e.g. see AGN.

The local Black Hole Mass Function

- Convolve Galaxy Luminosity functions with $M_{\text{BH}} = L_{\text{bul}}$ and $M_{\text{BH}} = \sigma$ to obtain the local BH mass function.
  - $M_{\text{BH}} = L_{\text{bul}}$ and $M_{\text{BH}} = \sigma$ provide consistent BH mass functions provided that dispersions are taken into account (shaded area indicates uncertainties)

$$\rho_{\text{BH}} \sim 4.1^{+1.9}_{-1.4} \times 10^5 \, M_\odot \, \text{Mpc}^{-3}$$


- In summary: $3-5 \times 10^5 \, M_\odot \, \text{Mpc}^{-3}$ (see Ferrarese & Ford 2005 for a review)
Transform to Mass Growth

- Take accretion rate and some model of initial BH mass distribution and watch them grow (Merloni et al 2006)
- Notice 'downsizing' big black holes grow first and small black holes later

Scenarios for Birth of SMBHs

How do SMBHs get started?
Detect $M \sim 10^9 M_\odot$ BH at $z \sim 7$ - need to grow fast!

Distinguish the 2 paths based on the fraction of small galaxies that today contain SMBHs

Greene 2012
Summary

• The most massive black holes today $M \sim 10^8-10^{10}$ M are no longer accreting a substantial amount of gas; thus, their masses are growing very slowly
• These black holes are found in the most massive galaxies with the most massive bulges
• Such galaxies are currently forming stars at a much smaller rate than in the distant past, and are lacking cold gas