Active Nuclei and Quasars

Françoise Combes
The growth of black holes with time

Rate=\text{Luminosity} / 0.1 \ c^2

Rate of growth of black holes=
Star formation rate / 3300

Madau & Dickinson 2014
Estimation of the black hole mass

Direct method:
Measure the gas or stellar velocity, very close to the black hole
Requires very high spatial resolution (Hubble)
This can be done on nearby galaxies, even for non-active black holes

For remote AGN, spectral and temporal resolution can replace the spatial resolution
Provided that the quasar continuum varies, and propagates in the accretion disk to the emission lines of the broad line region (BLR), close to the black hole

Technique called ‘reverberation mapping’
Kinematics of the ionized gas

- Dynamically measured mass: $1.5 \times 10^9 M_\odot$
- Velocity measured $\sim 400 \text{ km/s}$, at 8 pc from the BH (0.1” at 16 Mpc)
- At large distance, less precise measures

*Bower et al 1998*
Black hole in Andromeda (M31)

Mass determined by stellar kinematics

$M_{BH} = 10^8 M_\odot$
The stellar disk around the BH in M31

Separation P1-P2 = 0.5 \(^\prime\) = 1.8 pc, \(V=200\) km/s, Period 50 000 yrs
The two star clusters should merge?
In fact, it is an excentric stellar disk

P3 is a blue star cluster
Young stars of 200 Myr
Density and kinematics in the central 10pc

Velocity Dispersion

kinematic axis

HST infrared

TIGER / CFHT
Interpretation with $m=1$ mode

Wave rotating very slowly, with a period 2 Myr
Can persist 1000 $t_{\text{dyn}}$ (N-body simulation)

Peiris & Tremaine (2003)
Massless disk, not Self-consistent

Bacon et al 2001
N-body Simulation
**Disk velocity: P3 at 55°**

\[ M_{\text{BH}} = 1.4 \times 10^8 M_\odot \]

1" = 3 pc

Incertitude on the inclination 55° is different from The inclination of M31 \( i = 77° \)

*Lauer et al 2012*
NGC 4258: H$_2$O masers (1.3cm)

Radio jets

Size: qq mas
M = $4 \times 10^7 M_\odot$
D = 7.2 Mpc

1500 km/s
**Advantage of masers**

Stimulated emission, not spontaneous
Photons are in phase, and the light intensity is amplified

\[ E_2 - E_1 = \Delta E = h\nu \]

The very intense emission allows the use of VLBI
Very localised emission, close to the black hole
100 galaxies with masers
40 masers in disks
20 have triple spectra
10 with excellent precision

The measurement with masers could yield the Hubble constant with 1% precision
Conditions for maser measurement

- Dense \((10^8 - 10^{10} \text{ cm}^{-3})\)
- Hot \((300 - 800 \text{ K})\)
- Quiet \(\Delta v \sim \Delta v_D\)

- Masers = bright spots
  - Compact \((\theta < 1 \text{ mas})\)
  - High brightness temperature \(T_B \sim 10^7 - 10^{15} \text{ K}\)
  - \(\theta_x, \theta_y, v_{\text{los}}, d\theta_x/dt, d\theta_y/dt, dv_{\text{los}}/dt\)
- Proper motions
Other possible informations

Size of the accretion disk?
NGC 1068, Greenhill & Gwinn 1997

2nd population of masers
Tracing an outflow
Large opening angle

Circinus, Greenhill et al 2003
NGC 1277

too massive?

50% Mbulge!

Van den Bosch et al 2012
NGC 1277: an obese black hole?

Even with a factor 3, BH too massive

$M_{BH} = 1.7 \times 10^{10} M_\odot$ if $M/L^* = 6$

$M_{BH} = 0.5 \times 10^{10} M_\odot$ if $M/L^* = 10$

Scharwaechter et al 2015
Mass of the black hole and mass of the bulge

The two masses are proportionnal $M_{\text{BH}} \sim 0.5 \% M_{\text{bulge}}$

Some galaxies, in clusters, are above the line

They suffer from star formation Quenching, gas is stripped Galaxies are choked

Compatible with a large $M/L^*$ ratio

$\Rightarrow$ Very old stars

$\sim 100$ objects known with high precision
Reverberation mapping

- Variation of the central continuum luminosity
- The BLR reacts to variations (via photoionization) in a short time $\sim R/c$ with respect to $t_{\text{dyn}} = R/V$

Response time: travel time $t(R,\theta)$

$$t = \frac{R}{c}(1 - \cos \theta)$$

For a BLR in a thick shell the response to the continuum flash:

Bahcall et al 1972
Computation of the geometry and dynamics

Blandford & McKee (1982) were the first to use the term RM “reverberation mapping”

Variation of continuum $C(\tau)$ & of the line $L(v, t)$

The transfer function $\psi(v, t)$

$$L(v, t) = \int_{-\infty}^{\infty} \psi(v, t - \tau) C(\tau) d\tau$$

$\psi(v, t)$ contains the information on geometry and dynamics of the BLR.

The transfer function can be obtained by the Fourier transform and the convolution between the two light curves: $t \leftrightarrow \omega$

$$\psi(v, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega e^{-i\omega t} \frac{L(v, \omega)}{C(\omega)}$$

Inversion problem: difficult (or high S/N required!)
Spectrum of an active nucleus: $C(\tau), L(\nu,t)$

Balmer lines

PG0804+761

Hα

Continuum

Flux

Observed wavelength

Hβ

Other lines
Reverberation 1D map

Given the too scarce data, and the difficulty to measure small differences with large precision, the transfer function

$$\psi(\nu, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega e^{-i\omega t} \frac{\tilde{L}(\nu, \omega)}{C(\omega)}$$

is reduced to one dimension, or just a cross-correlation between light curves of continuum and line. The peak/centroid of the correlation is a measure of the size of the BLR – $R_{\text{BLR}}$.

$$CCF(\tau) = \frac{1}{N\sigma_C\sigma_L} \sum_t C(t)L(t + \tau)$$
Light Curves

$\Delta T = 13$ days

$\Delta t$

Mrk 335

Continuum

$F_{\lambda}(5100 \text{Å})$

$F(\text{H}\beta)$

HJD (-2450000)

jours

Grier et al. 2012
« Reverberation Mapping » RM

Each line of the BLR has an optimum radius

Isodelay surface

Time delay $\tau$

$\tau = (1+\cos\theta) \frac{R}{c}$

Line-of-sight velocity $V_{\text{LOS}}$ (km/s)

Simple hypothesis
Isotropic emission of the reing
Reverberation Mapping RM

\[ M = \frac{fr\sigma^2}{G} \]

\( r = \text{size, } \sigma = \text{velocity dispersion} \)

f Virial factor
More realistic models of reverberation

Take into account the large optical thickness of the BLR medium ➔ reflexion mainly towards the center

Red: Lyα
Green= CIV
Blue= HeII

Horne et al 2004
Inflow visible in several AGN

Grier et al 2013
Reverberation models, with flow

Reverberation mapping is a luxury method, the most exact, for a remote AGN. It then serves to calibrate the relation L-R, and therefore derive black hole masses for a much larger number.

⇒ Today project to determine the RM of 500 quasars, with OzDES (survey for dark energy)
Thirty years of data acquisition

The beginning Peterson (1988):

<table>
<thead>
<tr>
<th>Object</th>
<th>Radius (light-days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akn 120</td>
<td>&lt;30</td>
</tr>
<tr>
<td>NGC 4151</td>
<td>~6</td>
</tr>
<tr>
<td>NGC 5548</td>
<td>~30</td>
</tr>
<tr>
<td>3C 390.3</td>
<td>25-45</td>
</tr>
</tbody>
</table>

The first measures use only few epochs

The successive campaigns from 1990-2000:

- Campaign Lovers of Active Galaxies (LAG) (Robinson 1994).
- Campaign of Ohio state (Peterson et al. 1998).
- Campaign of Wise and Steward Observatories 17 quasars (Kaspi et al. 2000)
- Campaign Lick AGN Monitor Program (LAMP) Bentz et al 2009

In 2015 ~50 objects z<0.1 have reverberation mapping
Robotic monitoring Arp 151 (Mrk 40)

$M_{BH} = 6.2 \times 10^6 M_{\odot}$

200 days of observation on Sy-1 Arp151
With Las Cumbres Obs Global Telescope
LCOGT (California, Texas, Chili, Aus, SA…)

Time delay computed by cross-correlation

Valenti et al 2015
Delay depending on velocity (Arp151)

Dash: Virial enveloppe
\[ V^2 \tau_c / G = 1.2 \times 10^6 \, M_\odot \]

Inflow visible for H\(\alpha\) as soon as delay \(> 15\)d

It is important to frequently sample, which condition the spatial resolution obtained on the accretion disk

Bentz et al 2010
Robotic telescopes on the globe

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Coordinates</th>
<th>Elevation (m)</th>
<th>Code</th>
<th>Timezone</th>
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</thead>
<tbody>
<tr>
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<td>20° 42' 27&quot;N 156° 15' 21.6&quot;W</td>
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<td>ogg</td>
<td>UTC-10</td>
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<tr>
<td>McDonald</td>
<td>30° 40' 12&quot;N 104° 1' 12&quot;W</td>
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<td>elp</td>
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<td>Siding Spring</td>
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<td>UTC+10</td>
</tr>
</tbody>
</table>

15 telescopes: 2 x 2m, 10 x 1m, 3 x 0.5m

Google finances
BLR Relation between Size and Luminosity

Two fundamental quantities measured by RM

Peterson et al. (2014), Ho & Kim (2015) ~50 known systems

With a time delay in Balmer lines (mainly Hβ)
Characteristic size of the BLR = time delay * c

Luminosities obtained in optical, UV and X

Averaging measures obtained with all time delays of Balmer lines

Calibration of the L-R relation
Hβ – $R_{\text{BLR}}$ – Optical Luminosity (5100 Å)

$Q(H)$ nbr of ionizing photons

$U = \frac{Q(H)}{4\pi R^2 c n_e}$

$U$ flux and $n_e$

nbr of particules

$Q(H) = \int_{v_1}^{\infty} \frac{L_v}{h\nu} d\nu$

If the flux $U$ and $n_e$ are the same for all AGN, then

$R \sim Q(H)^{1/2}$

and if $L \sim Q(H)$

$R \sim L^{1/2}$

$R_{\text{BLR}} \propto [\lambda L_\lambda (5100 \text{ Å})]^{(0.54 \pm 0.03)}$

Slope 0.5 if all AGN have the same ionization degree

Bentz et al. 2013
Spin of super-massive black holes

Example of NGC 1365 (Risaliti et al 2013)
Mass $2 \times 10^6 \, M_\odot$
Method of relativistic reflexion, with the Fe Kα line: asymmetric excess 5-7 keV

+ 10-60 keV
+ absorptions
8 keV

Maximum $a \sim 1$  \( J \sim GM^2/c \)
speed $c$ reached at horizon
Variations in SR due to variability of absorption V a few 1000 km/s scales a few hours

Since 7-15/15-80 is constant the various E characterise the accretion disk ➔ size ~Rs
Spin of NGC 1365: maximum

It is delicate to separate the variations of a few hours due to the passage of absorbing clouds, from the relativistic signature of Fe Kα line.

The narrow Fe line is due to the reflection by diffuse gas far from the BH. The broad Fe line is the signature of relativistic effects. Absorbing clouds sometimes eclipse the blue side, sometimes the red, unveiling the relativistic distortion.

The high energy peak (30keV) is the reflection of the AGN continuum by the hot gas close to the BH (last stable orbit).

Close absorbers (hot) are always on the blue side (outflowing wind).
Different scales of Quasars

Animation: Zoom from the outer parts of the galaxy down to the nucleus

Scales varying over 10 orders of magnitude

Entering the galaxy – spiral arms, stars
1. Clouds of the NLR, colors white, blue
   Disk red/yellow is the molecular torus

2. Entering the BLR: clouds violet/green/yellow
   Accretion disk blue and white
   Jets are perpendicular to the accretion disk
**Accretion rate and radiation**

Hypothesis: **spherical**  \( \frac{dM}{dt} = 4\pi R^2 \rho v \) and \( c_s^2 = 2 \frac{GM}{R} \)

Bondi accretion rate, \( R = 2 \frac{GM}{c_s^2} \)

\[
\frac{dM}{dt} \approx (1.4 \times 10^{11} \text{ g/s}) \left( \frac{M}{M_\odot} \right)^2 \left( \frac{\rho}{10^{-24} \text{ g/cm}^3} \right) \left( \frac{c_s}{10 \text{ km/s}} \right)^{-3}
\]

Ignores the problem of angular momentum: in fact rotating disk

In a rotating disk of gas, the **viscous torques** could permit the gas to lose angular momentum and spiral towards the center

\[
\frac{dL}{dt} = F r
\]
Accretion disk, thin geometrically

The geometrically thin disk, optically thick, very efficient to radiate
The accretion disk can be considered as rings emitting like black bodies

Rate of dissipation, $D(R)$

$$D(R) = \frac{3GM\dot{M}}{8\pi R^3} \left[ 1 - \left( \frac{R_*}{R} \right)^{0.5} \right] = \text{flux of the black body}$$

$$ = \sigma T^4(R)$$

$$T_* = \left( \frac{3GM\dot{M}}{8\pi R_*^3 \sigma} \right)^{1/4} \quad T = T_* \left( \frac{R}{R_*} \right)^{-3/4} \quad \text{for} \quad R \gg R_*$$
Spectrum of the disk

Flux as a function of frequency, $\nu$

BBB = Big Blue Bump

Total disk spectrum

Annular BB emission

Log $\nu * F_{\nu}$

Log $\nu$
Black hole and accretion disk

For a non rotating BH, with spherical symmetry, the last stable orbit is at $3r_g$ or:

$$r_{\text{min}} = \frac{6GM}{c^2}$$

And when $R \gg R_*$

$$T = T_* \left( \frac{R}{R_*} \right)^{-3/4}$$
**Physics of accretion disks**

**Viscous forces** are the origin of exchange of angular momentum.
Most of the gas infalls to the center, a small fraction gets outside
conveying the essential of the momentum $L$.

→ **Viscous processes are dissipative**
They heat the medium, which radiates and loses energy.

The torque exerted from $R + dR$ on $R$:
$$ G(R) = 2\pi R h \nu \rho R^2 \frac{\partial \Omega}{\partial r} $$

$h$ is the disk thickness, $\nu$ the viscosity,
$\rho$ the gas density, and $\Omega$ its rotation frequency.

The hypothesis done by Shakura & Sunyaev (1973):
$$ \nu = \alpha c_s h $$

From dimensionnal arguments
→ Scale invariant solution
The atomic or molecular viscosity is negligible
Very diffuse gas, $10^3$ part/cm$^3$, very long mean free path $\sim$AU
$\tau_{\text{coll}} \sim 1$ yr

The viscosity is more macroscopic:
turbulence, magnetic field

Keplerian disk, differential rotation

$V^2 = GM/R \quad \Omega^2 = V^2/R^2 = GM/R^3$

$L = VR = (GMR)^{1/2}$
Magneto-rotational Instability (MRI)

The presence of magnetic field in a ionized medium: equivalent to link particules to each other \( \rightarrow \) springs

Differential rotation means that \( m_i \) rotates faster (\( \Omega \) larger, shorter period)

\( m_i \) tends to accelerate \( m_o \), and give it angular momentum. While it is \( m_o \) which has the largest momentum!
\( m_i \) falls to the center and rotates faster and faster!!

\( \rightarrow \) Very rapid instability, even (and mainly) for weak B fields

Balbus & Hawley 1991
Simulations of the MRI

Visualisation 3D of the accretion disk simulated with MRI

Cut of the accretion disk
Red, L larger than Keplerian
Blue, L lower
Magnetic field: tension

The strongly ionized fluid behaves like a conductor. With a B field (//Oz), its motion will create a E field 
\[ E = -v \times B, \] to cancel the force 
\[ \text{rot } E = dB/dt = \text{rot } (v \times B) \]
For a small displacement \( \delta r = v \delta t \) \( \Rightarrow \delta B = \text{rot } (\delta r \times B) \)
Or if B~cst, B frozen in the fluid \( \delta B = (B \cdot \text{grad}) \delta r \)

The field acts on a current J, with a force \( J \times B \)
\[ \text{rot } B = \mu J \]
The force is then equal to \( -\text{grad } (B^2/2\mu) + 1/\mu (B \cdot \text{grad}) B \)

Magnetic pressure, plus tension, equivalent to a spring

The fluid elements are like pearls on the B field lines
Necessity of an other model

Ho, 2005

BBB = Big Blue Bump

The model of thin disk, optically thick, explains the BBB
Does not exist in all AGN

Some have just a flux in power law

Others at low $L \sim 0.01 L_{\text{Edd}}$

have strong X- emission $> 100\text{keV}$
Low luminosity with respect to accretion

Some black holes do not radiate at the level permitted by their accretion rate:

For example SgrA* at the center of the Milky Way:

\[ \frac{dM}{dt} = 10^{-4} \frac{dM}{dt_{\text{Edd}}} \]

While \( L = 10^{-9} L_{\text{Edd}} \)

Same situation for all nuclei in nearby galaxies:

⇒ ADAF = Advection Dominated Accretion Flow
Energy balance

\[ \rho T dS = dQ = dQ^+ - dQ^- \]
\[ \rho T dS/dt = q^{adv} = q^+ - q^- \]

The accreted gas is heated by viscosity \((q^+)\) then cools by radiation \((q^-)\). Any heat excess is stored in the gas and travels with it in the flow, which represents the advection of energy \((q^{adv})\)

In the thin disk \(q^+ = q^-\) all is radiated away, \(L = 0.1 \text{ mc}^2\)

In an ADAF, \(q^-\) tends to zero, and \(q^+ = q^{adv}\) \(L << 0.1 \text{ mc}^2\)
Conditions for an ADAF

• An accretion disk becomes an ADAF if
  – The gas cannot radiate in a time scale lower than the accretion time. This occurs when \( \frac{dM}{dt} < 0.03 \frac{dM}{dt} \), where \( \frac{dM}{dt} = 2M_\odot /\text{yr} \) (\( \frac{M}{10^8 M_\odot} \)) (more precisely radiatively inefficient ADAF or RIAF)
  
  The gas heats, becomes quasi spherical (corona, \( \tau << 1 \))
  – The radiation is trapped (\( \tau >> 1 \)) and cannot escape in a time-scale lower than the accretion time. When \( \frac{dM}{dt} \sim \frac{dM}{dt} \) (geometrically thin disk)

• One only of these conditions implies an ADAF

sometimes ADAF only in the inner parts (disk outside)
In the ADAF regime, all the energy dissipated by viscosity is not radiated, but dragged into the hole.

Critical accretion rate ($\alpha=0.3$)
For $dM/dt$ lower $\Rightarrow$ ADAF

Narayan et al 1998
Possible disk shapes

1 Extended Corona
2 Flaring Blobs
3 Advection Dominated Disk
4 UV-Cloudlets

Haardt, 1997
Dynamo effect in the disks

- Magneto-rotational instability (MRI): $B_\phi, B_z \rightarrow B_r$
- Differential rotation: $B_r \rightarrow B_\phi$
- Magnetic flottability: $B_r, B_\phi \rightarrow B_z$

Y. Kato
Accretion disk and MRI

\[ \beta \equiv \frac{n k T}{(B^2 / 8\pi)} \]

Thermal/magnetic pressure

Initially poloidal B field

\[ \rightarrow \] structure with 3 phases

Hawley & Balbus 2002
Formation of the corona

The energy is transformed
-- accretion $\Rightarrow$ gravitational energy
-- Dynamo in the disk $\Rightarrow$ energie $B^2$

The loops in the field reconnect
$\Rightarrow$ Dissipation in thermal energy
Formation of the corona, Radiation, and possibility of inverse Compton with relativistic particules from the corona
Origin of X-ray emission

The heated accretion disk radiates \(\rightarrow\) UV bump, soft X-ray (temperature 12 millions K)
But the hard X-rays or gamma must come from elsewhere
Corona: billion K, MRI instability, B field
Primary and secondary X-rays

The first emission comes directly from the corona
Then part of it is reflected and comes from the disk

The Compton scattering polarises the X-emission

Reflection on the torus?
Comparison with IR emission
→ Geometry of the torus
Does the torus exist? Asymmetry or not?

Raban et al 2009
ADAF or ADIOS

\[ Be = \frac{v^2}{2} + \frac{\gamma P}{(\gamma - 1)\rho} - \frac{GM}{r - r_s} \]

The accretion energy cannot be radiated away
The gas heats, and even gains positive energy to escape (Bernouilli parameter Be positive)
\( \Rightarrow \) Loses gravitational bound, the disk evaporates

\( \Rightarrow \) Formation of a corona, but also jets
ADIOS = ADiabatic Inflow-Outflow Solution
Or CDAF Convection Dominated Accretion Flow
(hydro instability of a hot accretion disk)

\( \Rightarrow \) ADIOS more frequent!

Blandford & Begelman 1999

Su et al 2010
Simulations confirm the ADIOS model

Yuan, F et al 2012
Conclusions

How do we weight black holes?

-- Kinematics of ionized gas
-- Kinematics of stars
-- Masers in the accretion disk
-- Reverberation method, variability
-- Calibration Luminosity-size in Active Nuclei

Velocity of the BLR yields the mass

Physics of the accretion disk

-- Theory of the geometrically thin disk, optically thick
Black body radiation
-- ADAF, when radiation is inefficient
-- ADIOS, evaporation, formation of a corona