The impact of black holes on the Universe

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Outline

• Quasars and the growth of galaxy-centre BHs
• The physics of accretion discs
  – Accretion-driven jets
• Black holes and star formation through cosmic history
Part I: BH growth

- In SNe black holes with $M \sim 10 \, M_\odot$ form suddenly
- But we don’t think the BHs with $M > 10^6 \, M_\odot$ in galactic nuclei formed suddenly
  - they formed small and grew by feeding
- A massive BH can eat a star like the Sun whole
  - But galaxies cannot feed stars to their BH fast enough to account for growth to current masses
  - So galactic BHs must have grown by accreting gas
Soltan argument

- Suppose that when $M$ grows by $m$ energy $E = \kappa mc^2$ is released, where $\kappa \approx 0.1$ is the efficiency factor.

- Now in (large) unit volume $E$ released in Hubble time is (Soltan 1982)

$$E = \frac{4\pi}{c} \int dz (1 + z) \int dS \, S \, n(S, z)$$

- i.e., energy released per unit volume is easily inferred from $n(S,z)$, the number of sources at redshift $z$ per unit solid angle, flux density & redshift.

- The resulting mass density in BHs is $\rho = E/(\kappa c^2)$.

- Soltan predicted typical galactic BH mass from this mass density and the number density of galaxies $M \approx \rho/n_g$. 
Soltan revisited by Yu & Tremaine (2003)

- From counts of quasars in optical bands
  \[ \rho = 2.1 \times 10^5 \left( \frac{0.11}{\kappa} \right) M_{\odot} \text{Mpc}^{-3} \]

- From correlation between \( M_{\text{BH}} \) and the galaxy’s central velocity dispersion and Sloan Digital Sky Survey, mass density of BHs in galaxies is
  \[ \rho = (2.5 \pm 0.4) \times 10^5 M_{\odot} \text{Mpc}^{-3} \]

- The mass density of BHs agrees (amazingly!) well with value predicted by assuming quasars powered by accreting gas with efficiency \( \sim 10\% \)

- Caveat: role of obscured quasars (light absorbed but still contribute to \( \rho \))
Part II: Accretion discs

- BHs gigantic drains
- When washing-up water goes down the plughole, it swirls around in a vortex
- Similarly hurricanes, tornadoes
- Same happens when gas falls onto a star or BH

Kornmesser (ESO)
Disc dynamics

• Consider steady state: mass spirals in at rate $dm/dt$ shedding energy $E$ and angular momentum $J$ as it goes
• Material is on essentially circular orbits at all times
• Energy shed as mass moves in is radiated from disc’s upper & lower surfaces
• A viscous torque carries angular momentum to larger & larger radii
Disc dynamics

- Conceptually decompose disc into annuli
- Within an annulus deposition of energy by flowing matter gives power (rate of working)

\[ P_m = \frac{1}{2} \left( \frac{GM}{r} - \frac{GM}{r + \delta r} \right) \frac{dm}{dt} = \frac{GM}{2r^2} \frac{dm}{dt} \delta r \]
Disc dynamics

- Inner annuli rotate faster than outer annuli
- Each annulus has work done on it by annulus inside it, and does work on annulus outside it
- The difference between work done on an annulus and the work the annulus does turns out to give a power
  - \( P_{\text{visc}} = 3P_m \)
- Assume disc radiates as a black body (\( \sigma T^4 \) per unit area & time) so luminous power is \( P_L = \sigma T^4 (4\pi r \delta r) \)
- Now equate \( P_L \) to total power = \( 4P_m = (2GM/r^2)(dm/dt)\delta r \)
- Choose \( dm/dt \) to give characteristic BH growth time 100 Myr and solve for \( T \) and \( L \)
Temperatures of disc for $M = M_\odot$ or $M = 10^8 M_\odot$ BH

- Take $\frac{dm}{dt} = \frac{M_\odot}{100}$ Myr or $1 M_\odot/yr$
- At a given multiple of $R_s = 2GM/c^2$ the solar-mass BH disc is hotter by factor 100
- For quasar most L in UV rather than X or gamma rays
• Plotted: Luminosity at r’>r
• Accreting at 1 M$_{\odot}$/yr a galactic BH by far outshines its galaxy of ~$10^{11}$ stars
• 90% of L from inside Pluto’s orbit
• Consistent with quasars
You may be impressed
But you shouldn’t be!

• The stupendous E output of a quasar is degraded into visual or IR photons close to the BH

• These photons criss-cross intergalactic space without significant impact

• Quasars are just histrionics
Getting something done

• What provides the all important viscosity?
• Magnetic field!
• Field lines carry tension
• When lines are stretched, work is done on the field, which is amplified
• The disc’s plasma is effectively a perfect conductor
• Field lines are trapped within the plasma of the accretion disc
• Within a differentially rotating disc, field lines are constantly stretched and the field is amplified
Magneto-Rotational Instability (MRI)

- No matter how weak the field was originally, it is soon strong enough to modify the flow that was amplifying it
- In other words, it becomes capable of carrying dynamically significant $J$ outwards
Coronal heating

- The field doesn’t stay in the disc plane because:
  - B provides pressure \perp to field lines
  - Plasma can flow along but not across field lines.
  - A section of a line with less plasma is less weighed down, so B-pressure causes it to arch up, speeding flow of plasma from this section (Parker instability)
  - Soon there are loops of field connecting foot points in the disc that are in relative motion
Reconnection

- Field lines moving in opposite directions can reconnect.

As field geometry changes, E previously stored in the field is released.
- E used to accelerate particles and heat local plasma.
- So region above/below the disc becomes too hot to be confined by the gravitational field: it flows away in a wind.
Magnetic collimation

- Magnetic field lines collimate the flow parallel to the disc’s spin axis
- This physics is not fully understood but observations show it is scale-free and generic:
  - Accreting objects most readily detected by their bi-polar outflows
Accreting objects
proto-star Herbig Haro 30
Accreting objects
stellar-mass BH SS433

Blundell & Bowler 2004
Accreting objects
$10^8 \, M_\odot \, BH \, Cygnus\, A$
Modified accretion disc picture

- The wind feeding the jet carries m, E, and J away from the disc with the consequence that
  - Only a fraction of what falls onto the disc reaches the BH
  - The disc now has a mechanical power output: the jet
  - The radiative luminosity is smaller than we estimated
Mechanical vs radiative power

• Observations indicate that
  – Mechanical power can significantly exceed radiative power
  – Systems can switch rapidly between radiative and mechanical (quasar/radio) modes

• This best studied in solar-mass BHs because their timescales shorter by $10^8$ (yr for SS433 = 100 Myr for Cygnus A)
Part III: Black holes and star formation

- The rate of star formation has fallen dramatically since redshift \( z=2 \)
- The radiative luminosity of BHs in galaxies has tracked star-formation rate so \( L_{\text{QSO}} \propto \text{SFR} \)
- BHs are now mostly in mechanical mode

Madau & Dickinson 2014
Cool-core clusters

• In clusters like Virgo, T of plasma falls by factor \( \sim 3 \) as the centre is approached
• The cooling time of the plasma becomes much shorter than age of system
• But there is much less gas at \( T < 10^6 \text{K} \) than expected if the plasma were steadily cooling
• Conclude: plasma radiates but does not cool
Jets @ work in Virgo

- Jets driven by accretion onto a BH with $M = 4 \times 10^9 \, M_\odot$ at centre of the galaxy M87 replaces energy radiated by dense plasma near the cluster centre.
- 4/5 of the clusters baryons are invested in this plasma.
- The BH keeps it too hot to form stars.
- The rate of accretion onto central BH ($M \sim 4 \times 10^9 \, M_\odot$) should vary as $T^{-5/2}$, so BH can act as a thermostat for intergalactic plasma much as nuclear fusion thermostats the Sun.

Virgo A (=M87) at the centre of the Virgo cluster.
Inhibiting galaxy growth

- The scale of DM clustering has continually grown
- But BHs have prevented the formation of supermassive galaxies
Conclusions

• BH growth mirrored growth of stellar populations
• Energy released during BH growth mostly radiated by quasars with little impact
• This a natural consequence of BHs and stars feeding off cold, dense gas
• BH growth and SFR have declined strongly since z=2
• Not because of a shortage of gas but a shortage of cold gas
• There are 2 modes of accretion: radiatively and mechanically efficient
• Magnetic field key in both modes but especially important in mechanical mode
• After z=2 more & more BHs shifted to mechanical mode
• They then truncated galaxy growth by thermostating intergalactic plasma
• Hence BHs have played a major role in shaping the visible Universe