This week at Astro 3303

Lecture 12, Oct 04, 2017

- Pick up PE#12

- Today:
  - HW#4 discussion
  - AGN & supermassive black holes

- Reading: Chapter 3.5 & 10.4-10.5 of textbook
NGC1068/M77

→ HW#4 discussion
The standard model of AGN

Components:

- **Supermassive Black Hole (SMBH)**
  \[ r = R_s \text{ [typ. } 10^{-5} \text{ pc]} \sim M_{BH} \text{ [} 10^6-10^{10} \text{ } M_{\odot}] \]

- **Accretion Disk (UV/X-ray emission):**
  \[ r \sim 10^{-3} \text{ pc}, n \sim 10^{15} \text{ cm}^{-3}, \nu \sim 0.3c \]

- **Jets (radio sync. emission):** core/jet/lobes/hotspots
  \[ r \sim 0.1 - 10^6 \text{ pc} \]

- **Broad Line Region (BLR; allowed lines):**
  \[ r \sim 0.01 - 0.1 \text{ pc}, n \sim 10^{10} \text{ cm}^{-3}, \nu \sim \text{few } 10^3 \text{ km s}^{-1} \]

- **(Dusty) Torus (feeding/obscuration; IR-mm em.):**
  \[ r \sim 1 - 100 \text{ pc}, n \sim 10^{3} - 10^6 \text{ cm}^{-3} \]

- **Narrow Line Region (NLR; forbidden/allowed lines):**
  \[ r \sim 100-1000 \text{ pc}, n \sim 10^{3} - 10^6 \text{ cm}^{-3}, \nu \sim \text{few } 100 \text{ km s}^{-1} \]

...+ host galaxy (spiral/elliptical/merger?)
Effects of the orientation to AGN
Unification of AGN

Assumption:
All AGN types are the same but looked at from a different point of view

<table>
<thead>
<tr>
<th>Radio-Quiet</th>
<th>Face-on</th>
<th>Edge-On</th>
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<tbody>
<tr>
<td>Radio-Loud</td>
<td></td>
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<tr>
<td>Radio-Quiet</td>
<td>Sy1</td>
<td>Sy2</td>
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<tr>
<td>QSO</td>
<td></td>
<td>FIR Galaxy?</td>
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<tr>
<td>BL Lac</td>
<td></td>
<td>FR-I</td>
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<tr>
<td>BLRG</td>
<td></td>
<td>NLRG</td>
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<tr>
<td>Quasar</td>
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<td>FR-II</td>
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This idea dates back to, at least, Rowan-Robinson (1977), and became popular in the mid-80s (reviews by Lawrence 1987, Antonucci 1993, Urry & Padovani 1997, Goodrich 2001).
# Geometry of AGNs

The diversity of AGN types can be explained by the aspect angle under which we observe the AGN plus evolutionary effects.

<table>
<thead>
<tr>
<th>AGN type</th>
<th>line of sight</th>
<th>evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL Lac</td>
<td>directly into the jet</td>
<td>M strong, jet</td>
</tr>
<tr>
<td>radio loud quasar</td>
<td>$\theta \approx 20^\circ - 70^\circ$</td>
<td>M maximum, jet with $v_{jet} \sim c$</td>
</tr>
<tr>
<td>radio galaxy</td>
<td>$\theta \approx 20^\circ - 90^\circ$</td>
<td>M mean, jet with $v_{jet} &lt; c$</td>
</tr>
<tr>
<td>radio quiet quasar</td>
<td>$\theta \approx 20^\circ - 70^\circ$</td>
<td>M maximum, no jet</td>
</tr>
<tr>
<td>Seyfert</td>
<td>$\theta \approx 20^\circ - 70^\circ$</td>
<td>M weaker, no jet</td>
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<table>
<thead>
<tr>
<th>AGN type</th>
<th>emission lines</th>
<th>host galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>broad</td>
<td>narrow</td>
</tr>
<tr>
<td>strong radio galaxy</td>
<td>strong/weak</td>
<td>strong/weak</td>
</tr>
<tr>
<td>weak radio galaxy</td>
<td>weak</td>
<td>weak</td>
</tr>
<tr>
<td>BL Lac</td>
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<td>none/weak</td>
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</tr>
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<td>none, strong/weak</td>
<td>strong/weak</td>
</tr>
</tbody>
</table>
Support for unification: hidden emission lines

Some Sy-2s show broad lines in polarized light

(e.g., NGC 1068; Antonucci & Miller 1983):

The fraction is still unclear since the observed samples are biased towards high-pol broad-band continuum objects.

(Bill Keel`s web page w/ data from Miller et al.1991; Capetti et al. 1995)
Obscuring torus: Hot electrons scatter photons from the BLR near the nucleus to the observer. Optically-thick dust torus shields direct line-of-sight to the nucleus.

⇒ Radiation will escape anisotropically from the AGN.

Hence, Sy-2 look a bit like Sy-1 in polarised light.
Support for unification: ionization cones

NGC 5728
Hubble Space Telescope
Wide Field / Planetary Camera

The ultraviolet emission comes from the accretion disk, lighting up a cone of glowing gas in the galaxy to the left. Only the cone of ultraviolet light can escape from the cavity in the accretion disk where the black hole lies; in other directions, the light is absorbed by the disk. (From STScI, modified by G. Rieke)
Support for unification: broad IR lines

25% of Sy-2s show some broad component in the IR

There are searches for broad-recombination lines in the near-IR spectrum of Sy-2s, where the extinction affects the emitted spectrum less. They are detectable if $A_V \leq 11$ mag for Pa$\beta$, $A_V \leq 26$ mag for Br$\gamma$ and $A_V \leq 68$ mag for Br$\alpha$. (Goodrich et al. 1994).
Type 1 (Broad Line) AGN

*Type 1 AGN* have bright continua and bright, broad (in velocity) emission lines. They are (with increasing radio luminosity):

- Seyfert I galaxies
- Radio quiet quasars (QSOs)
- Broad Line Radio Galaxies (BLRG)
- Radio loud quasars (i.e. the older designation of quasars)

Other than radio (and optical) luminosity little distinguishes Seyfert IIs from radio quiet quasars or BLRGs from radio quasars.

Broad lines are due to gas close to the black hole whereas narrow lines can arise in distant regions (ionized by the nuclear source)
Type 2 (Narrow Line) AGN

Type 2 AGN have weak continua and narrow emission lines.

- **Radio quiet type 2** include (with increasing luminosity)
  - Seyfert 2
  - Narrow Emission Line X-ray galaxies (NELG)
  - Ultraluminous IR Galaxies (ULIRG; type 2 features are expected to be seen in these dusty galaxies), Type 2 Quasars

- **Radio loud type 2** = Narrow-Line Radio Galaxies (NLRG)
  - Fanaroff-Riley type I radio galaxies (FR-I)
    - Symmetric radio jets whose intensity decreases from the nucleus
  - Fanaroff-Riley type II radio galaxies (FR-II)
    - Highly collimated jets with well defined sharp edged lobes and hot spots.
    - Correlated with higher radio luminosity
Unusual objects ("type 0"):
Blazars: AGN with relativistically-beamed jets aligned with line of sight
BAL (broad absorption line) QSOs: polar AGN outflows at small opening angles
⇒ Can be described by the same phenomena
Where are the Type 2 Quasars?

- Only recently have we gained the technology to find these “hidden” quasars.
- Sensitive X-ray telescopes look for high energy photons penetrating the dust torus. (but: may be Compton-thick)
- Mid-IR observations: torus is transparent.
- Bright lines in the near-IR

Poletta et al. 2006, 2007
Banerji et al. 2012
Summary

• AGN come in many forms and shapes. However some of their properties cross AGN-type “boundaries”

• This has led to a “Standard Model” of AGN

➔ In the center of the AGN host is a black hole surrounded by an accretion disk, clouds of gas and a dusty torus, from which (sometimes) a jet emerges.

• AGN types are the results of mostly their orientation but also different physical circumstances (why a jet?)

other relevant parameters: power, age, radio loudness, SMBH mass, host galaxy properties
Arguments in Favor of SMBHs as the Engines of AGN

Theoretical arguments for SMBHs in AGN:
- Radiation pressure: Lower Limit on $M_{BH}$
- Radiation Efficiency of Accretion on BHs

Observational evidence for SMBH in Galaxies/AGN hosts:
- High central stellar velocity dispersions
- Mega-maser disks
- Radial Velocities from Ionized Gas
- Broad Iron (Fe) Kα lines (relativ. accretion disk)
- Reverberation mapping
- Sgr A* in the Galactic Center (next week)
Accretion onto Black Holes

- Photons possess a momentum $p_\gamma = \hbar v/c \Rightarrow$ photons exert radiation pressure outwards.

- Sir Arthur Eddington recognized that there is a natural limit to the luminosity $L$ that can be radiated by a compact object of mass $M$. The limit arises because the attractive gravitational force acting on any electron-ion pair and the repulsive force contributed by radiation pressure are both proportional to $r^{-2}$. This limit is called the Eddington luminosity of the BH.

- When the luminosity exceeds the Eddington limit, the gas will be blown away by radiation and hence will not be accreted onto the BH.

- The Eddington Luminosity is the maximum radiative luminosity that a star (or BH) can have and still remain in hydrostatic equilibrium.

- Now consider a case where a BH is accreting matter from its surroundings. In order that accretion can occur, the luminosity of the BH must be less than the Eddington Luminosity. Otherwise, the radiation pressure will halt the accretion.
Consider a parcel of gas located some distance from a central source of luminosity $L$.

- The flux from the central source at this distance is:

$$ F = \frac{L}{4\pi D^2} $$

- The momentum carried by a photon is $E/c$, so that the outward momentum flux ("photons pressure") is:

$$ P_{\text{rad}} = \frac{F}{c} = \frac{L}{4\pi D^2 c} $$

- The outward force due to radiation pressure is:

$$ F_{\text{rad}} = \sigma_e \frac{L}{4\pi D^2 c} $$

where $\sigma_e$ is the Thomson electron scattering cross section.
Radiation Pressure: BH mass limits

(Long-term) stability of the AGN gas requires that the gravitational force exceeds or equals the radiation pressure from the AGN:

\[ F_{\text{grav}} \geq F_{\text{rad}} \]

\[ \sigma_e = \text{Thomson (electron scattering) cross section} = 6.65 \times 10^{-25} \text{ cm}^2 \]

Radiation Force on an electron

\[ \vec{F}_{\text{rad}} = \sigma_e \frac{L}{4\pi r^2 c} \hat{r} \]

Gravitational Force on electron plus proton pair (medium must be neutral)

\[ \vec{F}_{\text{grav}} = -\frac{GM \cdot (m_p + m_e)}{r^2} \hat{r} \]
Radiation Pressure: BH mass limits

**Eddington Limit:**

\[ L \leq \frac{4\pi G c m_p}{\sigma_e} M_\bullet \approx 6.31 \times 10^4 M_\bullet \text{ erg s}^{-1} \approx 1.26 \times 10^{38} (M_\bullet / M_{\text{sun}}) \text{ erg s}^{-1} \]

This is known as the Eddington limit, which can be used to establish a minimum for the mass of the BH: \[ M_E = 8 \times 10^5 L_{44} M_{\text{sun}} \]

For typical Seyfert galaxies \( L \approx 10^{44} \text{ erg s}^{-1} \), so \( M_{\text{Sy}} \approx 8 \times 10^5 M_{\text{sun}} \)

For QSOs \( L \approx 10^{46} \text{ erg s}^{-1} \), so \( M_{\text{QSO}} \approx 8 \times 10^7 M_{\text{sun}} \)

The Eddington luminosity is the maximum luminosity emitted by a body of mass \( M_{BH} \) that is powered by spherical accretion.
Why “black hole”? 

• With an Eddington mass $>10^8 \, M_{\text{sun}}$ and size constraints $<1\,\text{pc}$ from variability one can derive a robust lower limit for the central mass density:
  $$\rho > 10^8 \, M_{\text{sun}} \, \text{pc}^{-3}$$

• For comparison remember that
  - in our vicinity there are only a few stars within a parsec distance.
  - star clusters “only” have densities of $\sim 10^2 - 10^6 \, M_{\text{sun}} \, \text{pc}^{-3}$
  $\rightarrow$ AGN powered by SMBH

• NB: The term “black hole” was invented by John Wheeler in 1967 well after the concept was invented.

• Note: the critical mass density for a black hole is:
  $$\rho_{\text{BH}} = M_{\text{BH}} / (4/3 \, \pi \, R_S^3) = 1.8 \, M_8^{-1} \, \text{g cm}^{-3}$$
  compared to the mass density of water: 1 g cm$^{-3}$
What is a black hole?

• A black hole is a concentration of mass so large, that even light cannot escape its gravitational attraction

• A black hole has only two parameters (we ignore charge):
  – the mass $M_{BH}$ and
  – the spin (angular momentum) $0 \leq a \leq 1$ in units of $M_{BH} c R_g = G M_{BH}^2 / c$.

• A non-rotating black hole ($a=0$) is called a Schwarzschild hole

• A rotating black hole ($0 < a \leq 1$) is called a Kerr hole.
We can also write the equation in more convenient units as:

\[ R_S = \sim 3 \text{ km per solar mass} \]

Schwarzschild radius:
- 1 solar mass: \( \sim 3 \text{ km} \)
- 1 earth mass: \( \sim 9 \text{ mm} \)
Fueling Black Holes

• Fundamental process in AGN: conversion of mass to energy, at some efficiency $\eta$. Thus, the energy available from mass $M$ is: $E = \eta Mc^2$. The energy is emitted by the nucleus at a rate $L = \frac{dE}{dt}$, providing the rate at which energy must be supplied to the nuclear source by accretion:

$$L = \eta \dot{M} c^2$$

• Mass accretion rate:

$$\dot{M} = \frac{L}{\eta c^2} \approx 1.8 \times 10^{-3} \left( \frac{L_{44}}{\eta} \right) M_\odot \ \text{yr}^{-1}$$

• When mass falls onto a black hole, grav. potential energy $U$ is converted to kinetic energy. If released through conversion to radiation, this gives a rate:

$$L \approx \frac{dU}{dt} = \frac{GM}{r} \frac{dm}{dt} = \frac{GM \dot{M}}{r}$$

and thus, that $\eta \sim \frac{M}{r}$ – i.e., higher toward smaller radii

• The potential energy available from a mass particle $m$ falling to within $5 \ R_S$ is:

$$U = \frac{GMm}{5R_S} = \frac{GMm}{10GM/c^2} = 0.1mc^2$$

$\Rightarrow \ \eta_{\text{acc}} \sim 10\%$ to convert rest mass to energy, compared to the efficiency of nuclear fusion of $\eta_{\text{nucl}} \sim 0.7\%$! (more detailed calculation: 6\%-42\% for $0<a<1$)

$\Rightarrow$ For a quasar: $L_{QSO} = 10^{46}$ erg/sec; with $\eta = 10\%$: $\dot{M} = 2 \ M_{\odot} \ \text{yr}^{-1}$ (rel. small).
Accretion Disk Temperature

• Assume an optically thick medium and local dissipation, and a geometrically thin disk. The virial theorem \( 2E_{\text{kin}} + U = 0 \) gives that 50% of the release from potential energy goes into heating the gas, and 50% are released. Thus:

\[
L = \frac{G M \dot{M}}{2r} = 2\pi r^2 \sigma T^4 \quad \text{or} \quad T = \left( \frac{G M \dot{M}}{4\pi \sigma r^3} \right)^{1/4}
\]

• More correctly taking into account that energy is likely dissipated in the disk through friction as a consequence of turbulent viscous torques, one obtains:

\[
T(r) \approx 6.3 \times 10^5 (\dot{M} / \dot{M}_E)^{1/4} M_8^{-1/4} \left( \frac{r}{R_S} \right)^{-3/4} \text{ K.}
\]

⇒ less massive black holes peak at higher temperatures/energies

Using Wien’s law:

⇒ Quasar accretion disks typ. peak at \( T \sim 10^5 \text{ K} \), i.e., at short UV wavelengths
⇒ Less luminous, massive black holes (Seyferts) peak at \( T > 10^7 \text{ K} \), i.e., soft X-rays
⇒ Stellar black holes (XRBs) peak at hard X-ray wavelengths
SMBH Masses: Stellar Kinematics in M31

- Velocity dispersion increases to 250 km/s toward center
- Radial velocities increase to 200 km/s before passing through center
- Kormendy (1988) derived a mass of about $10^7 M_{\text{sun}}$

*Figure 1. Velocity $V(r)$ (bottom) and velocity dispersion $\sigma(r)$ (top) profiles along the nucleus major axis of M31. (Taken from Kormendy and Richstone 1995).*
M87 (Massive Elliptical): Gas Kinematics

HST kinematics of innermost region in M87:

- Radial Velocity measurements using spectroscopy of emission lines of ionized gas
- Ford et al. 1994 derive a mass of $2.4 \times 10^9 \, M_{\odot}$ within the inner 18 parsecs of the nucleus
NGC 4258: Mega-Masers

$\text{H}_2\text{O}$ mega-maser @ 22 GHz detected in NGC 4258 in a warped annulus of $0.14 - 0.28$ pc and less than $10^{15}$ cm of thickness, with a beaming angle of $11^\circ$ (Miyoshi et al. 1995, Maloney 2002).

Combining the Doppler velocities ($\pm 900$ km s$^{-1}$) and the time to transverse the angular distance ($0.14$ pc) gives the mass of the nucleus:

$3.9 \times 10^7 M_{\odot}$ within $r \leq 0.012$ pc
Nearby spheroidal galaxies show a tight correlation between the mass of the central black hole and the velocity dispersion (and mass) of the stellar spheroid:

\[ M_{BH} \sim 0.1 \sigma_v^4 \quad \text{and} \quad M_{BH} \sim 1/700 \ M_{\text{bulge}} \] (linear)

At a given mass, more compact bulges contain more massive black holes. Thus, if baryons collapsed and dissipated above average efficiency, the galaxy contains a more massive black hole.

To maintain this relation, there has to be some mechanism that makes black holes and stellar mass in galaxies form and grow “in sync”.

=> what is this growth regulating/quenching mechanism? AGN feedback? Stellar/SF feedback? => are these relations a coincidental snapshot in time, or do they exist at all cosmic epochs?
Radio Galaxies and Radio-Loud Quasars

Radio galaxies & radio-loud quasars: the most powerful radio sources

(Usually) extended (or very extended!) radio emission with common characteristics (core-jets-lobes)
Typically hosted by elliptical (early-type) galaxies nearby

\[ \text{Unexpectedly high amount of energy involved!} \]

The radio contributes only to a minor fraction of the energy actually released by these AGNs.
(ratio between radio and optical luminosity $\sim 10^{-4}$)
However, the kinetic power in jets can be a significant fraction of the accretion energy
Magneto-Hydrodynamic Jets

• Emitted from axis of rotation, inner part of accretion disk

• Acceleration of charged particles from strong magnetic fields and radiation pressure

• Synchrotron Radiation
  – Produces radiation at all wavelengths especially at radio wavelengths

• Possible source of ultra-high energy cosmic rays and neutrinos

• Basic MHD mechanism:
  – Blandford (1976); Lovelace (1976)
  – Acceleration by rotating black holes
    Blandford & Znajek (1977)
  – Acceleration by rotating (thin) accretion disks
Radio Jets: Relativistic Beaming

Bulk motion, when relativistic, results in
- Beamed emission \((1/\gamma = (1-v^2/c^2)^{-1/2})\)
- Doppler boost \((I_\nu/\nu^3\text{ is an invariant under Lorentz transformation})\)
- Blue Shift \((\nu = \Delta \nu_{\text{comoving}}/\gamma)\)

- e.g., for a modest \(v = 0.97c (\gamma\sim4)\), the forward (backward) flux can be boosted (reduced) by a factor of 1000 along l.o.s.!

- Transverse super-luminal motion is seen in many flat-spectrum radio sources

- In some cases there is excellent alignment from milli-arcsecond to the arcminute scale (from nucleus to lobes).

![Image](image_url)

Relativistic Doppler factor:

\[ D = \frac{1}{\gamma (1 - \frac{v}{c} \cos \theta)} = \frac{\sqrt{1 - \beta^2}}{1 - \beta \cos \theta} \]

\(\Rightarrow\) Flux boosting: \(I_\nu = D^3 I_\nu_{\text{comoving}}\)
M87 Relativistic jet: Super-luminal motion
- Apparent velocity greater than the speed of light!
  \[ v = \frac{d\theta}{dt} \cdot D \]

The optical jet of the nearby radio galaxy M 87 (the central galaxy of the Virgo cluster in a distance of about 17Mpc). The jet is highly collimated and shocks are visible within the jet. The emission is synchrotron radiation from relativistic electrons.

\[ \rightarrow \text{PE#12 has more details!} \]
Apparent super-luminal motion

An observer at point A sees a radio blob move from B to B’

In the co-moving frame, the blob moves to B’ in time $\delta t$

$\Rightarrow$ visible angular separation to observer at distance D:

$$\Delta \varphi = \frac{v \delta t \sin \theta}{D}$$

The radio blob moves at relativistic velocity $v$ of almost c

$\Rightarrow$ almost catches up with photons emitted at B

$\Rightarrow$ time difference for blob to move from B to B’:

$$\Delta t = \delta t - \beta \delta t \cos \theta = \delta t (1 - \beta \cos \theta) \quad \text{where} \quad \beta = \frac{v}{c} \quad \text{[no Lorentz factor} \gamma, \text{since the system is at rest to obs.]}$$

The apparent transverse velocity inferred by observer at distance D thus is:

$$\beta_T = \frac{v_{\text{app}}}{c} = \frac{1}{c} D \frac{\Delta \varphi}{\Delta t} = \frac{1}{c} \left[ \frac{v \delta t \sin \theta}{\delta t} (1 - \beta \cos \theta) \right] = \frac{\beta}{1 - \beta \cos \theta}$$

$\Rightarrow$ For $\gamma = (1 - \beta^2)^{1/2} > 3$: $v_{\text{app}} > c$ for most angles
Reprocessed Radiation

AGN produce a lot of ionizing radiation $\leq$ Accretion Disk

Radiation is intercepted by gas & dust and re-processed

- **Dust Torus:** IR radiation
- **Gas:** Emission lines
  - Narrow Lines $\Rightarrow$ NLR
  - Broad Lines $\Rightarrow$ BLR
- **X-ray fluorescence**

Sanders et al. 1989
Spectral Energy Distribution of Seyferts, QSOs, BLRGs

Radio Quiet Quasars

IR bump  Big Blue Bump
Sub-mm break
1 µm minimum
Soft X-ray Excess

Radio-Loud Quasars

Radio
The Blue and IR bumps

- $L_{\text{IR}}$ contains up to $1/3$ of $L_{\text{bol}}$
  $L_{\text{BBB}}$ contains a significant fraction of $L_{\text{bol}}$

- IR bump due to dust re-radiation, BBB due to black-body emission from the accretion disk

- The UV 3000 A bump at 4000-1800 A:
  - Balmer Continuum
  - Blended Balmer lines (Balmer limit: 3647 A)
  - Forest of Fe II lines

- The soft X-ray excess is likely related to the accretion disk properties, but the origin is still subject to debate
Infrared Continuum

- In most radio-quiet AGN, there is evidence that the IR emission is *thermal* and due to heated *dust*.

- However, in some radio-loud AGN and blazars, the IR emission is *non-thermal* and due to *synchrotron* emission from a jet.
Emerging picture

- The 2\(\mu\)m-1\(\mu\)m region is dominated by *thermal emission* from dust (except in some radio-loud AGN and blazars, where the IR emission is *non-thermal* and due to *synchrotron* emission from jets).

- Different regions of the IR come from different distances because of the *radial dependence* of temperature.

- 1\(\mu\)m minimum: *hottest dust* has \(T_d \sim 2000\) K (dust sublimation \(T\)) and is at \(\sim 0.1\) pc (generic feature of AGN).

*From Stefan Boltzmann law:*

\[
\Rightarrow R_{\text{dust}} = \sqrt{\frac{L_{\text{IR}}}{2\pi\sigma T_{\text{dust}}^4}} = 0.4\ \text{pc} \left(\frac{L_{\text{IR}}}{10^{46}\ \text{erg sec}^{-1}}\right)^{0.5} \left(\frac{T_{\text{dust}}}{2000\ \text{K}}\right)^{-2}
\]
Infrared Continuum: Evidence

Obscuration:

- Many IR-bright AGN are obscured (UV and optical radiation is strongly attenuated)
- IR excess is due to re-radiation by dust

IR continuum variability:

- IR continuum shows same variations as UV/optical but with significant delay
- Variations arise as dust emissivity changes in response to changes of UV/optical that heats it
Dust Reverberation Mapping

- Optical flux varied by factor ~20

- IR variations follow ~1 year later

- IR time delays increased with increasing wavelength (cooler dust)

Evidence for dust (torus) a light-year from the AGN nucleus, with decreasing $T$ as function of radius