1932: KARL JANSKY
Is assigned the task of identifying the noise that plagued telephone calls to Europe

1935: noise is identified as coming from inner regions of Milky Way
MANY YEARS GO BY……

1960: a strong radio source is detected (3C48)
Allan Sandage takes a spectrum in optical

It’s the weirdest spectrum I have ever seen
WHAT IS A SPECTRUM?

Hydrogen
Oxygen
Carbon

EMISSION as a function of wavelength or frequency:
LINES + CONTINUUM

SPECTRA ARE THE “ID CARDS” OF ASTRONOMICAL OBJECTS
The spectrum of 3C48 was ‘weird’ because lines of known elements didn’t appear to have the ‘right’ wavelength.

The lines in the spectrum are redshifted: the source is very far away from us! (4.5 billion light years!!!)

The luminosity of the source is ENORMOUS!!!
The “light travel time” argument:

- Suppose source doubles (or halves) brightness in 1 day
- If source is bigger than 1 light-day then no signal can coordinate the variation
- Therefore source must be be smaller than 1 light-day

A catch: Random (uncoordinated) fluctuations may make source appear to vary more quickly than light travel time - but only rarely.
Case of 3C273: the source varies over a timescale of a month

The source produces a luminosity 100 times that of a galaxy in a volume which is $10^{18}$ times smaller!!!

WHAT IS THIS COMPACT ENGINE THAT CAN OUTPUT SO MUCH ENERGY???

NOT a dense concentration of stars (the spectrum is too different)
MIN. MASS FROM ENERGY OUTPUT

- We see lots of active galaxies
- Their lives can’t be too short (> few million yr)
- Luminosity $\times$ Lifetime = Total energy output
- Total energy output $< \text{Total mass } \times c^2$
- “Central Engine” $> \text{few million solar masses}
PUTTING IT TOGETHER

- Variability → small size
- Energy output → large mass

COMBINATION OF SMALL SIZE AND LARGE MASS → BLACK HOLE
How can massive black holes generate such a high luminosity?

- By accreting mass through an accretion disk
- Via electromagnetic processes that tap the spin energy of the black hole (probably have to do with jet production)
JETS: very common in Active Galaxies; often surrounded by radio lobes

Jet in the Active Galaxy M 87
[Image: Hubble/NASA]

Cygnus A - radio emission
[Image: VLA]
ONE-SIDEDNESS

• Many jets appear “one-sided” but lobes are symmetric: Why?

ACCEPTED EXPLANATION: RELATIVISTIC MOTION

One-sidedness due to beaming (aberration + Doppler) effect
A blob of gas that radiates photons equally in all directions appears to be shining preferentially along its direction of motion if it is moving relativistically.
What happens to the supermassive black holes at the centers of galaxies once they become starved of fuel?

Where are they now?

They dwell in the centers of nearby galaxies, including the Milky Way.

How do we know?

From dynamical constraints on the presence of a large mass within a small volume.
Strongest evidence comes from the motion of the stars in the vicinity of the galactic center (SgA*)
A source, called Sgr A*, is observed at the location of the Black Hole (emission from hot gas in the vicinity of the Black Hole)

Flares are often observed; they likely signal the swallowing by the BH of a star which has gone too close to the BH and has been tidally disrupted.

[Ghez et al. 2004]
IN EXTERNAL GALAXIES THE MOTION OF GAS CLOUDS AROUND THE CENTRAL SUPERMASSIVE BLACK HOLE CAN BE TRACKED DUE TO THEIR **MASER EMISSION**. THE MOTION OF THESE CLOUDS IS USED TO INFER THE MASS OF THE BLACK HOLE.

MASER = Microwave Amplification by Stimulated Emission of Radiation

*Image from “Gravity’s Fatal Attraction” by M. Begelman & M. Rees*
NGC 4258: its nucleus harbors a black hole of 36 million solar masses
SOMBRERO GALAXY: nuclear BH weighs 1/2 billion solar masses
BIG open question:

How are supermassive Black Holes formed?
Popular belief: "seed" BHs from collapse of first stars, believed to be very massive (VMS)

The first dying stars with masses on the order of several hundred solar masses leave remnant BHs with masses $M_{BH} \sim 100 M_{\text{sun}}$

[Image courtesy of M. Volonteri]
SMBHs are formed as a result of mergers of smaller BHs during the process of hierarchical galaxy formation.

Seed BHs at very early times in the universe history.

Growth with merger and accretion in conjunction with the process of galaxy evolution.

[Image courtesy of M. Volonteri]