Elliptical & Active Galaxies

Bulges & Dwarf ellipticals
The AGN population & Supermassive black holes

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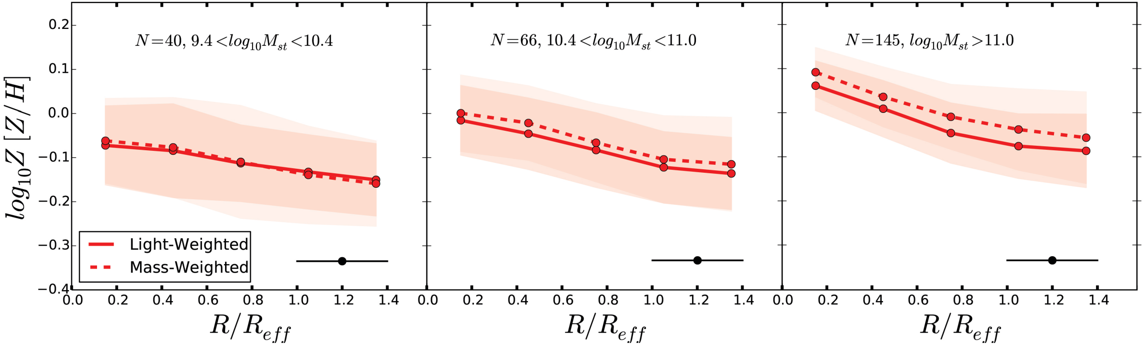
Gradients in elliptical galaxies

The outskirts of elliptical galaxies are bluer than their centers.

Absorption line indices exhibit gradients that are consistent with a metallicity gradient: higher metallicities in the center.

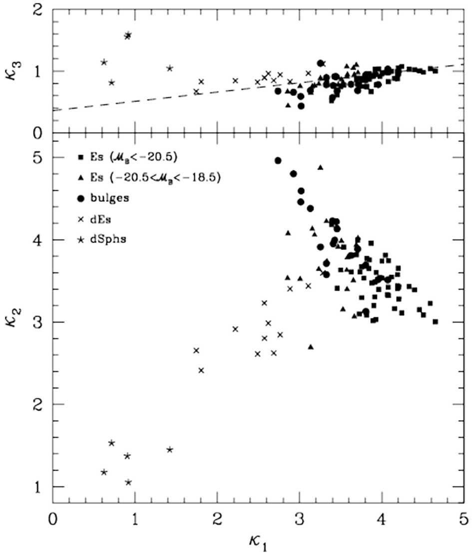


Lacerna et al. (2000)

Stellar population properties of elliptical galaxies

- Ellipticals exhibit passive stellar evolution after an initial star formation episode
- More massive ellipticals formed stars earlier and over a shorter time scale
- Ellipticals in dense environments formed stars earlier than similar stellar mass ellipticals in less dense regions.
- More massive ellipticals are more metal-rich.
- The central regions are more metal-rich than the outskirts.

Similarities between bulges, ellipticals, and dwarfs



Formation of massive galaxy bulges

Massive galaxy bulges likely formed in a similar manner as intermediate luminosity ellipticals, since they share so many similar properties:

- Flattened by rotation
- Relationship between surface brightness profile and luminosity
- Color-magnitude, metallicity-luminosity relations
- Fundamental Plane relations
- $M_{\rm BH}$–σ relation

Formation of dwarf ellipticals and dwarf spheroidals

It is not clear how dwarf ellipticals and dwarf spheroidals are formed, as all the current scenerios predict properties which differ from those observed.

Wet mergers of dIrrs The same formation scenerio as intermediate luminosity ellipticals, just with smaller progenitors. *They would be located everywhere, not just within clusters.*

Gas stripping (dIrr $\rightarrow$ dE/dSph) Ram pressure strips gas from dIrr as it enters the cluster environment. *They would still be supported by rotation.*

Galaxy harassment (S $\rightarrow$ dE/dSph) High-speed impulsive encounters transform low surface brightness disks into dE/dSph. *While galaxy harassment does increase the internal velocity dispersion, rotation would still dominate.*

Tidal stripping (E $\rightarrow$ dE/dSph) Ellipticals are tidally stripped in the clusters. *The dwarfs would have high metallicities and black hole masses which would sit well above the* M_{BH}–σ *relation.*

Normal galaxies v. Active galaxies

The emission of “normal” galaxies is dominated by the stellar population. Their SED is therefore just thermal radiation, spanning $\sim$4000Å to $\sim$20,000Å.

The emission of active galaxies, on the other hand, extends to much shorter and longer wavelengths than is expected from a collection of stars, gas, and dust. This emission covers the entire electromagnetic spectrum and is therefore *not* thermal in origin.

In addition, the optical and ultraviolet parts of the spectra of active galaxies contain strong, broad emission features not present in the spectra of “normal” galaxies.

This non-thermal emission comes from a region only a few pc across at the centers of these active galaxies. This central region is known as the active galactic nucleus (AGN).

Despite its small size, an AGN’s luminosity is often much brighter than that of the entire host galaxy!

Properties of an AGN

An object is considered to be an AGN if it has at least one of these following properties:

- Compact nuclear region much brighter than a region of the same size in a normal galaxy
- Non-stellar (non-thermal) continuum emission
- Strong (possibly broad) emission lines
- Variability in the continuum emission and/or the emission lines on a relatively short timescale

Types of AGN

Several types of galaxies are known to have an AGN.

The following types were discovered by radio astronomers, and thousands are now known:

- **Quasars** (and QSOs)
- **Radio galaxies**

These were discovered by visible-light astronomers, and hundreds are now known:

- **Seyfert galaxies**
- **Blazars** (BL Lacertae objects and OVVs)

Note that active galaxies are vastly outnumbered by normal galaxies.

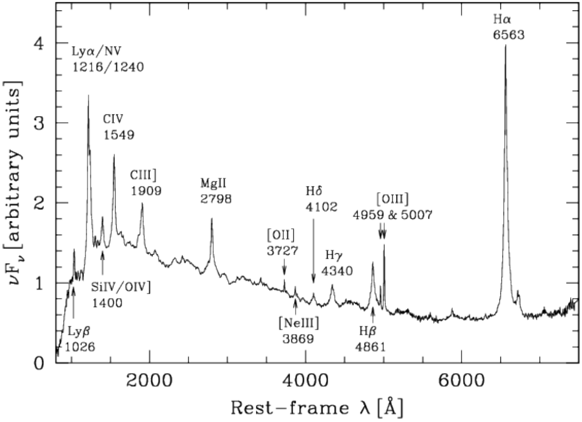
Seyfert galaxies

Discovered in the 1940s by Carl Seyfert, these are **spiral galaxies** with starlike nuclei, often brighter than the rest of the galaxy, with ionized gas associated with the centers.

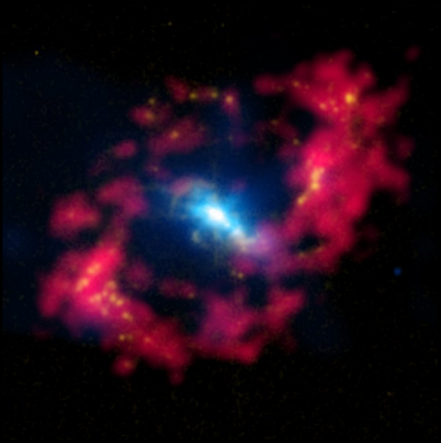
Type 1 Seyferts Very broad recombination lines ($\sim 10^3$ km/s in width) associated with the nuclei. Example: NGC 4151.

Type 2 Seyferts Narrow-line spectra ($\lesssim 10^2$ km/s) at the nucleus. Example: NGC 1068.

Low-luminosity Seyfert galaxies are LINERs (low-ionization nuclear emission line regions).



Seyfert galaxies



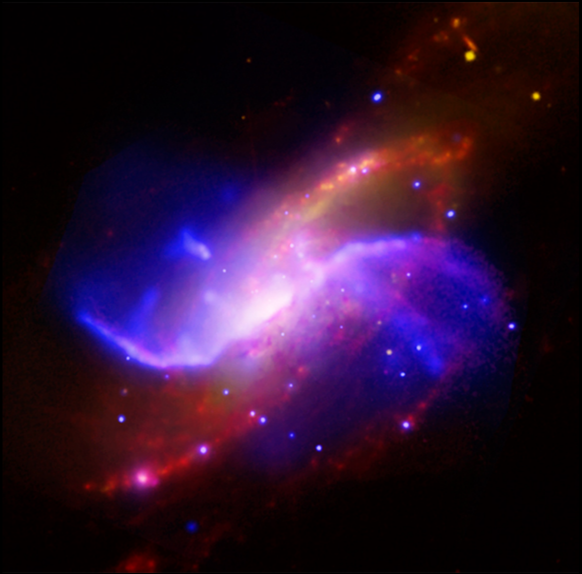
Left: NGC 4151, the "Eye of Sauron," showing X-rays in blue (NASA/CXC), HII emission in yellow (Kapteyn Telescope), and HI emission in red (VLA). Right: NGC 1068, shown in an X-ray/visible composition from NuSTAR and HST.

Seyfert galaxies

M106 (NGC 4258)

- Very short jet, oriented roughly along the galaxy's axis, seen in nucleus.
- The rest of the jet is apparently entrained in the disk of the galaxy.

M106 in X-rays from jet-driven shocks (blue) and visible light from normal galactic processes (red). Second visible image from R. Gendler.



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Radio galaxies

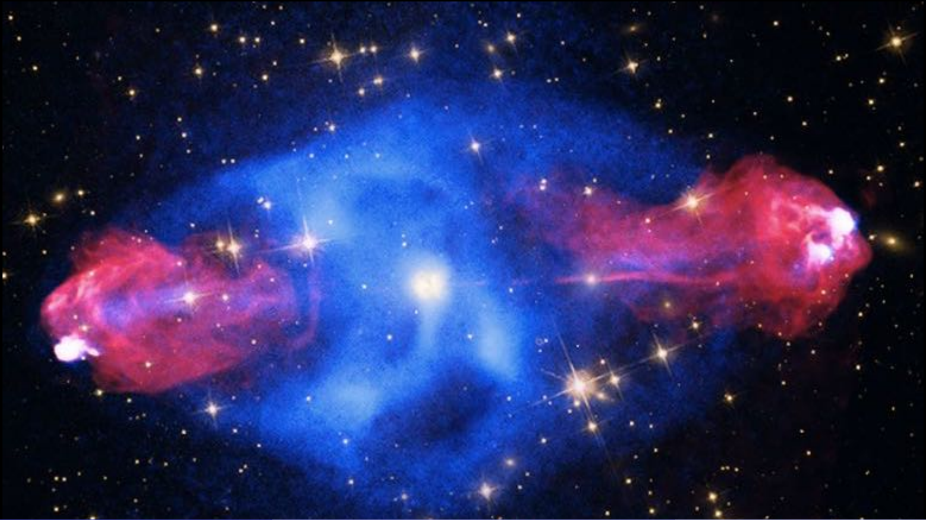
Discovered in the 1950s, radio galaxies appear to consist of a pair of extended radio lobes on either side of a visible, elliptical galaxy.

As radio interferometric measurements improved, radio galaxies were shown to also possess compact and pointlike central objects coincident with the galactic nuclei and connected to the lobes by narrow, usually straight jets.

The lobes themselves have fine filamentary structure. Many have hot spots as the ends of the jets, and one lobe is always brighter than the other.

The archetypical radio galaxy: 3C 405 (Cygnus A)

X-ray/optical/radio overlay of Cygnus A, the first known radio galaxy (Baade & Minkowski 1954). Visible image from HST-WFPC2; X-ray from NASA/CXC (Wilson 2000); radio from NRAO/AUI (Perley 1984).



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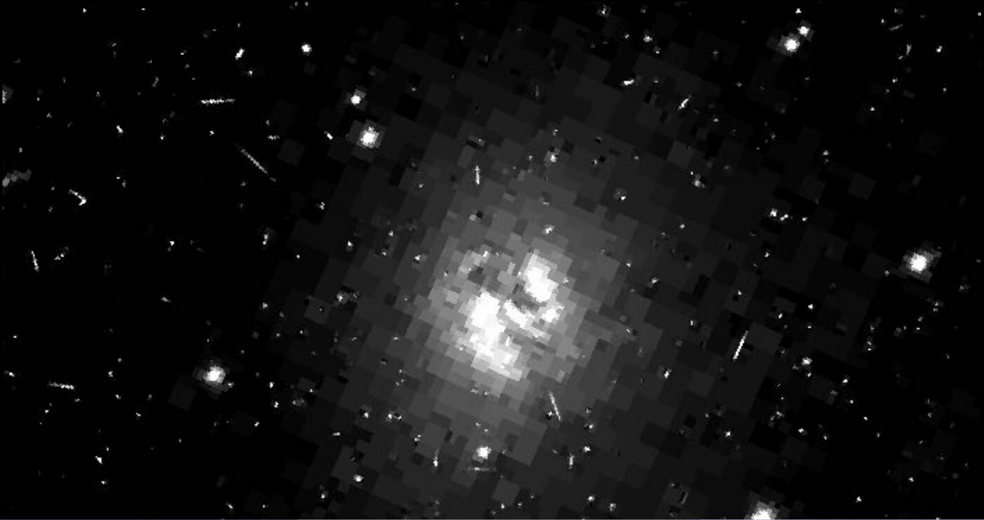

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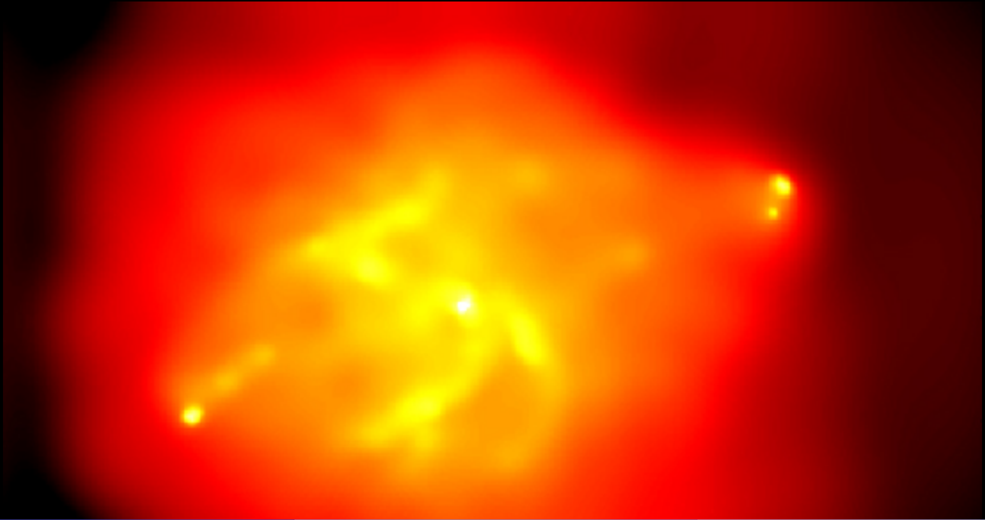

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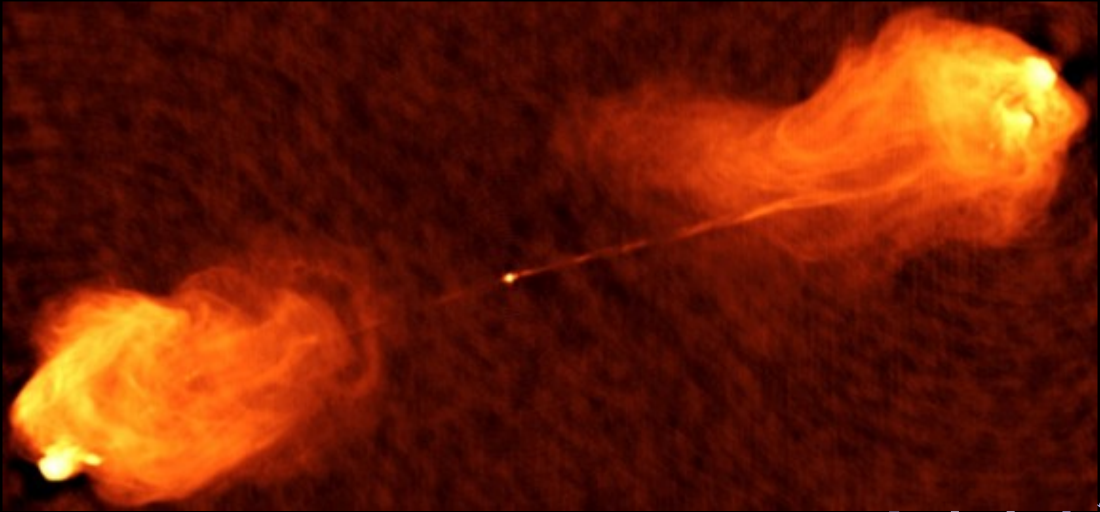
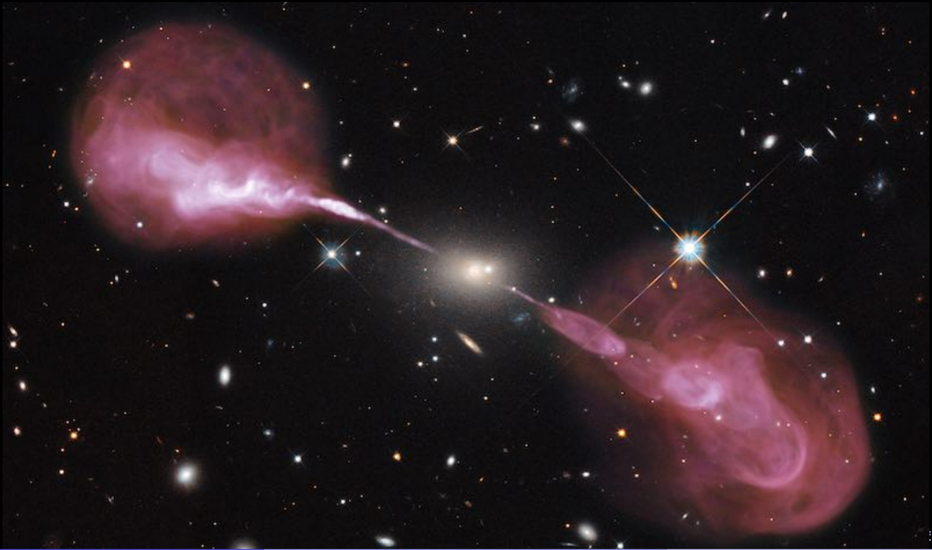


3C 348: Hercules A

Supergiant elliptical galaxy 3C 348 plus radio source Hercules A (VLA + HST).



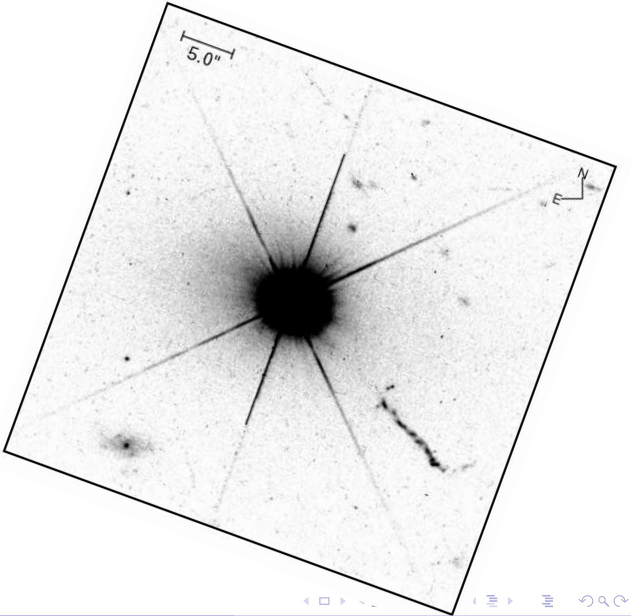
Quasars and QSOs

Quasar = quasi-stellar radio source

QSO = quasi-stellar object

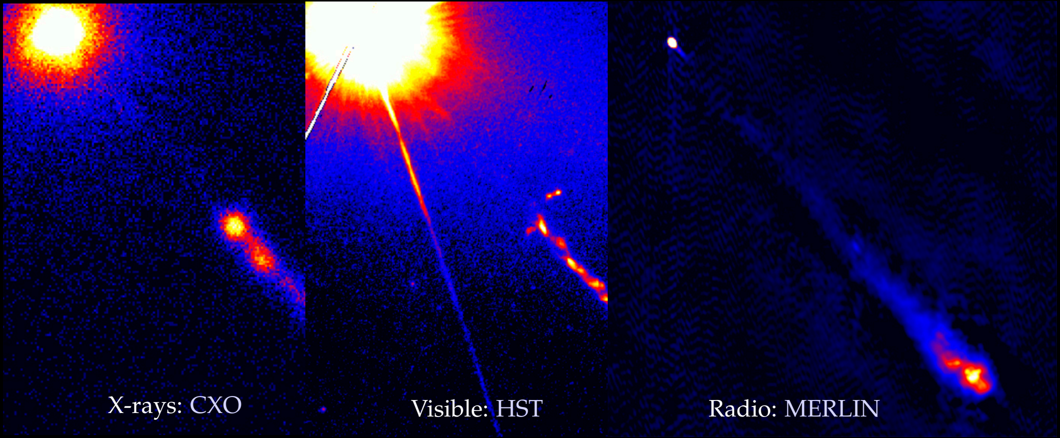
These objects are unresolved, luminous, blue, and highly variable.

They have a single narrow jet, often exhibiting apparent superluminal motion.



Hubble-ACS photo-negative image of 3C 273 (from J. Bahcall, Princeton).

The archetypical quasar 3C 273



The luminosity of 3C 273, the first QSO discovered, is dominated by its starlike central core, visible in all three images above. It also has a jet but no "counterjet" visible on the other side of the quasar.

Blazars

Blazars are bright and starlike. Only recently has very faint luminosity been detected around them to indicate that they are the nuclei of galaxies.

The spectra from blazars are smooth, making it hard to measure Doppler shifts. That is why BL Lacertae was first thought to be an object in the Milky Way (Hoffmeister 1929) until the host galaxy was observed in the 1960s (Schmitt 1968).

- OVVs (optically violent variables) are blazars with strong emission lines present. It is thought that these are the same as BL Lac objects whose main source of luminosity is fainter at the moment (so that the emission line features are not washed out by the continuum).

Most blazars are strong pointlike radio sources with significant variability. Stars are not. This was the first real indication that blazars are distant galaxies.

In fact, the variability implies a huge luminosity produced in a very small volume, implying the presence of a supermassive black hole.