Quasars and AGN

Survey of Astrophysics A110

3C 273

Jet

10 arcsec
Quasars and AGN

**Goals:**
- What are quasars and how do they differ from galaxies?
- What powers AGN’s.
- Jets and outflows from QSOs and AGNs

**Discovery of Quasars**
- **Radio Observations of the Sky**
  - Reber (an amateur astronomer) built the first radio telescope in 1936.
  - Strong radio emission was detected from the Sgr A, Cas A (Galactic) and Cyg A (extragalactic). Identified as star-like.
  - Cyg A has strong emission lines and lies at a redshift $z=0.057$ (220 Mpc for $H_0=75$ km s$^{-1}$ Mpc$^{-1}$). cyg A has $10^7$x radio luminosity of our galaxy.
  - Schmidt (1963) showed that some of the radio stars were not in our own Galaxy (for 3C 273) - quasi-stellar radio sources (*quasars*). Now denoted as **QSOs** (radio bright and radio quiet).
**High Redshift Objects**

- **Relativistic Redshifts**
  
  - Redshifts of quasars have been measured over $z=6$. Using the standard redshift relation we have to explain velocities greater than the speed of light!
  
  - We move back to special relativistic form for redshift. It is not a linear equation.

  \[
  \frac{\lambda - \lambda_0}{\lambda_0} = z = \sqrt{\frac{c + v}{c - v}} - 1
  \]

- $\lambda$: wavelength observed
- $\lambda_0$: restframe wavelength
- $v$: apparent velcity
- $z$: redshift
- $c$: speed of light

- As $v \to c$ redshift $\to$ infinity

- For the highest redshift QSO ($z=5.01$) the increase in the wavelength of the H$\alpha$ emission line is a factor of $6.01$ ($656.2$ nm $\to$ $3.94$ $\mu$m).

- The apparent recessional velocity is

  \[
  \frac{v}{c} = \frac{(z + 1)^2 - 1}{(z + 1)^2 + 1}
  \]

- For $z=5.01$ $v$ is $95\%$ of the speed of light.
<table>
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<tr>
<th>$z$</th>
<th>$v/c$</th>
<th>Distance (Mpc)</th>
<th>Distance ($10^9$ ly)</th>
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<td>1.00</td>
<td>4130</td>
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Note: This table assumes a Hubble constant $H_0 = 70$ km/s/Mpc, a matter density parameter $\Omega_m = 0.3$, and a dark energy density parameter $\Omega_\Lambda = 0.7$ (see Chapter 28).
Luminosities of QSOs

- From the distance modulus and the redshift distance relation we can calculate the luminosities of QSOs.
- QSO 3C 273 has a luminosity of $10^{40}$ W or $2.5 \times 10^{13} \, \text{L}_\odot$. Our Galaxy has a luminosity of $10^{37}$ W. QSOs are amongst the brightest objects in the sky.
- Radiation in not thermal (i.e. a blackbody spectrum). The spectrum of a QSO has a power law form from synchrotron radiation (acceleration of relativistic electrons).

\[
f_v \propto \nu^{-0.7}
\]

- $f_v$: flux per unit frequency
- $\nu$: frequency
- The strong emission lines come from the ionization of rapidly moving clouds of Hydrogen.
- The non-thermal spectrum seen in QSO spectra is indicative of the spectra seen from black holes.
- QSOs are powered by massive black holes at the center of a galaxy (host galaxy).
Synchrotron radiation

Blackbody radiation

Intensity

Frequency
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(a) Host galaxy

(b) Quasar
Other galaxy
Merging galaxy

(c) Dust and gas tail
Quasar
– Variability of QSOs

• QSOs vary on time scales of a few days, weeks and months.
• This limits the possible size of a QSO.
• Imagine a QSO 1 yr across (0.36 pc).
• If the QSO luminosity varies instantaneously then the light from the part of the QSO closest to the observer would arrive 1 year before the light from the furthest part of the QSO.
• A sudden flash of light would appear as a slow rise and fall in intensity over the course of a year.
• Variations on the time scale of a day mean that the QSO must be less than 200 AU.
• QSOs must be small and massive to produce a large amount of energy and vary over a short time period.
Bridging the gap between QSOs and galaxies.

- QSOs are 1000x brighter than normal galaxies why are there not intermediate luminosity galaxies?
- There are. A class of galaxies called Seyferts (I and II).
- These galaxies have bright compact nuclei (Active Galactic Nuclei - AGN) and have luminosities from $10^{36}$-$10^{38}$ W.
- They make up approximately 10% of luminous spiral galaxies (this number is not certain).
- They tend to have weak radio emission.
- Some Elliptical galaxies also have strong radio emission (radio galaxies). They tend to have jets of high energy particles (from the center of the galaxy) emitting synchrotron emission.
- These jets produce radio lobes on either side of the Elliptical galaxy (e.g. Centaurus A).
• **Powering AGNs**
  
  **Massive black holes as central engines**
  
  • Lynden-Bell (1968) suggested than supermassive black holes might power AGNs.
  
  • The luminosity that a black hole can output through accretion of matter is given by the Eddington limit.

\[
L_{\text{Edd}} = 30,000 \left( \frac{M}{M_\odot} \right) L_\odot
\]

• \( L_{\text{Edd}} \): Eddington luminosity
  
  \( M \): Mass of black hole
  
  • For luminosities \( L > L_{\text{Edd}} \) the radiation pressure will stop material accreting onto the black hole.
  
  • For QSOs 3C 273 \( L = 3 \times 10^{13} L_\odot \). If this is the Eddington limit (the smallest black hole that can produce this luminosity) then the black hole mass \( M = 10^9 M_\odot \).
  
  • Supermassive black holes may have been observed in the Andromeda Galaxy (M31) where rapidly rotating stars surround the core of the galaxy (suggest \( 10^7 M_\odot \) system within 5 pc of the galaxy center.)
- **Density of supermassive black holes**

  - Supermassive black holes are not hard to create - they do not require a massive star or supernovae.
  - Using simple Newtonian arguments we can estimate the density of matter in a supermassive black hole.
  - The density of matter is given by \( \rho = \frac{3M}{4\pi R^3} \)

  - The mass of a black hole is related to its Schwarzschild radius by
    \[ R = \frac{2GM}{c^2} \]

  - Substituting for the radius we can estimate the relation between density and mass of a black hole.
    \[ \rho = \frac{3c^6}{32\pi G^3 M^2} \]

  - For a “normal” black hole \( M=10M_\odot \) the density is \( 10^{17} \text{ kg m}^{-3} \) (1/5th density of a neutron star).
  - For a supermassive black hole with \( M=10^9 \, M_\odot \) the average density is only 10 kg m\(^{-3}\) (10x density of air).
 Blob at $A$

4 light-years

$5\text{ light-years}$

Blob at $B$, six years later

First pulse of light reaches Earth in 2000

Second pulse of light: emitted six years later, but has 4 fewer light-years to travel — reaches Earth two years after the first pulse, in 2002

To Earth

Actual speed of blob = $\frac{5}{6}c$

a View from above
b View from Earth

Apparent speed of blob = 1.5c

2000 → 3 light-years ← 2002