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Supermassive Black Holes:

The most powerful high-energy sources in the universe are the active galactic nuclei (AGN's), and their most distant siblings quasi-stellar radio sources (quasars), which are sprinkled throughout the universe. The earliest members of this class, discovered in the early 1960's, were known as pointlike radio emitters with very unusual spectra featuring several prominent emission lines. The recognition that these lines were highly redshifted led to the realization that the objects producing them must be distant and extremely luminous, typically producing radiation at a rate of $L_q \sim 10^{46}$ erg s^{-1}. Their radiative output is highly variable, from days to years, in all observable wavebands. Light travel-time arguments then constrain their origin to be a highly compact volume, with a scale on the order of the solar system. Already at the end of 1960's, the conversion of mass into radiation via accretion onto a black hole was recognized as the most efficient source of energy production. Let us briefly review the beautiful argument by Lynden-Bell here.

Suppose that a typical quasar shines for a time $t_q \sim 10^9$ yr, a likely prospect considering that these objects are sometimes observed at redshifts higher than 6. The total energy output during its lifetime is then $E_q \sim L_q t_q \sim 3 \times 10^{62}$ erg. The efficiency of producing energy via nuclear reactions is $\sim 0.7\%$, and hence the nuclear waste left behind by a quasar would be (at least) $M_q \sim 4 \times 10^{10}\ M_\odot$. The underlying engines of quasars have a size smaller than $R \sim 10^{15}$ cm (as pointed out above). The gravitational potential energy of M_q compressed into a radius R is

$\frac{GM_q^2}{R} > 10^{65}$ erg. This implies that gravitational contribution is the dominant source of energy production.

There are now several additional lines of evidence in support of the supermassive black hole paradigm for these sources. These include measurements of the speed of objects with an almost perfect Keplerian motion around the central source, as well as measuring the Doppler broadening of emission lines in the X-ray spectrum. These indicate the presence of a large mass, in the form of a supermassive black hole, compressed into a rather small volume.

We may get an idea of how many supermassive black holes may be lurking in the cosmos. The X-ray detections by Chandra indicate a large number of suspected supermassive black hole, which one can use and infer an overall population of ~300 million spread throughout the Cosmos. Yet these X-ray detections speak only of those particular sources whose orientation facilitates the transmission of their high-energy radiation. The actual number must be higher since many of these objects are obscured from view. This inference may be drawn from a consideration of the faint X-ray background pervading the intergalactic medium. A simple census shows that to produce such an X-ray glow with quasars alone, for every know source there must be ten more obscured ones.

The most widely accepted view today is that quasars are found in the active nuclei of galaxies hosting a supermassive black hole. They actually reside in the nuclei of many types of galaxies, from normal to highly disturbed (by collisions or mergers). Because of their intrinsic brightness, the most distant quasars are seen at a time when the universe was a small fraction of its present age. The current distance record is held by the quasar ULAS J1342 + 0928, which has a redshift of $z = 7.54$. The number of quasars rose dramatically from this epoch to a peak around 3 billion years later, falling off sharply toward the present time.

Between the quasar realm (extending to distances ~12 Glyr) and the nearby galactic nuclei (restricted to distances of a few Mlyr or less), the supermassive black hole accrete at a rate between $\sim 10\, M_\odot\, yr^{-1}$ (in the former) to $\sim 10^{-2}\, M_\odot$ (in the latter). Since quasars seem to have peaked around 10 Gyr ago, while light from galaxies originated after the universe was 2-4 Gyr older, and since the most distant quasars seem to be the most energetic ones, at least some supermassive black holes must have existed near the very beginning.

Supermassive Black Holes in AGN's:

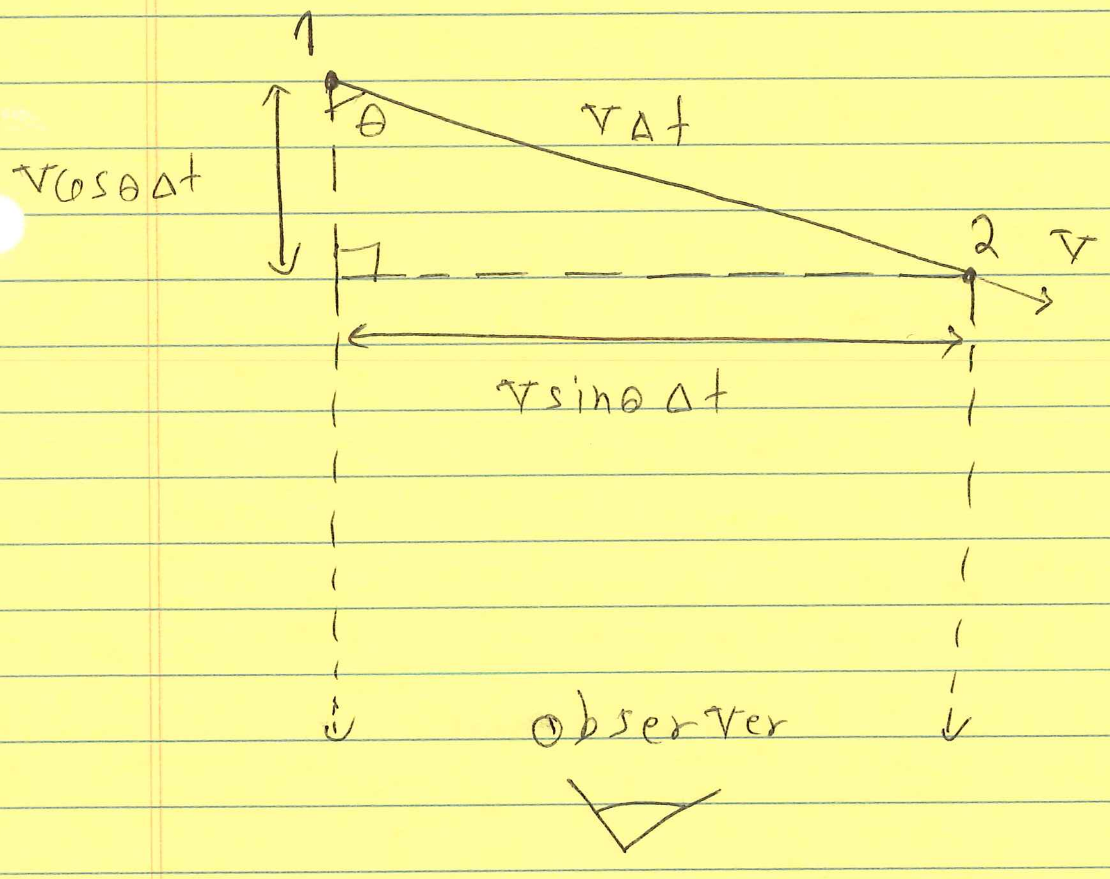
Astronomers have tended to subdivide AGN's into groups defined primarily by their specific observational characteristics. Quasars are the most luminous (and most distant) members of AGN's. They are spatially unresolved in optical photographs, implying an angular size smaller than ~7". Quasars themselves are subdivided into radio-quiet and radio-loud categories, with only about 15%-20% of all quasars being radio-loud. Blazars comprise a very interesting subclass of radio-loud AGN's. They are characterized by their unusually rapid variability, their strong and variable optical linear polarization, and their flat radio spectrum and featureless broad non-thermal continuum. Many blazars are superluminal sources, i.e., show apparent transverse velocities with magintudes greater than c. These supermassive black holes are believed to have their jets oriented almost exactly along the line of sight. Their emission is therefore greatly enhanced by Doppler boosting effect, and their observed variability time scale greatly shortened.

To see this, we recall that a time interval $\Delta t'$ in the frame of emitting plasma becomes $\Delta t \sim \gamma^{-1} \Delta t'$ in our frame. Correspondingly, the radiation is blueshifted according to $\nu \sim \gamma \nu'$, and the specific intensity is considerably enhanced $I_\nu \sim \gamma^3 I_{\nu'}$. As a result, the total intensity follows:

$$I = \int I_\nu \, d\nu \sim \gamma^4 \int I_{\nu'} \, d\nu' = \gamma^4 I'$$

There is now ample evidence for a Lorentz factor of $\gamma \sim 10$ (or more) in the relativistic jets. This implies an enhancement of at least ~10,000 in the observed flux.

The apparent superluminal transverse velocities are also due to the velocity component along the line of sight. Suppose that we observe a blob of relativistic electrons emitting synchrotron radiation as they move from point 1 to point 2 as shown below:



The apparent duration of the pulse received on the Earth is:

$$\Delta t_{app} = \Delta t - \frac{\Delta t\, v\cos\theta}{c} = \Delta t\left(1 - \frac{v\cos\theta}{c}\right)$$

The apparent transverse velocity will then be:

$$v_{app} = \frac{v \Delta t \sin\theta}{\Delta t_{app}} = \frac{v \sin\theta}{1 - \beta\cos\theta} \qquad \left(\beta \equiv \frac{v}{c}\right)$$

The maximum apparent velocity occurs at $\cos\theta_c = \beta$:

$$v_{max} = \gamma v$$

One can therefore get $v_{max} \gg c$ in this way. An informative survey whose sample include many objects in the AGN class show that apparent speeds of jets extended out to 34c for blazars. For quasars, v_{app} is between 0 and 10c for most sources.