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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 more distant siblings quasi-stellar radio sources (quasars), sprinkled throughout the cosmos. The earliest members of this class, discovered in the early 1960's, were known as pointlike radio emitters with very unusal 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 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 elegant argument by Linden-Bell.

Suppose that a typical quasar shies for a time $t_q \sim 10^9$ years, a likely prospect considering that these objects are sometimes observed at redshifts higher than 6. The total energy output during its liftime then is $E_q \sim l_q t_q \sim 3\times10^{62}$ erg. The efficiency of producing energy via nuclear reactions is $\sim 0.7\%$, so the nuclear waste left behind by a quasar would be (at least) $M_q \simeq 4\times10^{10} M_\odot$. The underlying engines of quasars have a size smaller than $R \sim 10^{15}$ cm. The gravitational potential energy of $4\times10^{10} M_\odot$ compressed into such a volume is $\frac{GM_q^2}{R} > 10^{65}$ erg. This implies that gravitational contraction 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 holes, which one can use and infer an overall population of ~300 million spread throughout the cosmos. Yet, these X-rays 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 known source there must be ten more obscured ones. The all pervasive X-ray haze now points to supermassive black holes as the agents behind perhaps half of all the universes radiation produced after the big bang.

The most widely accepted view today is that quasars are found in the active galactic nuclei of galaxies hosting a supermassive black hole. They actually reside in the nuclei of many different types of galaxies, from normal to those 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 mere fraction of its present age. The current distance record is held by an object with a redshift of $z \sim 6.42$. The number of rose dramatically starting from this epoch to a peak around 2.5 billion years later, falling off sharply toward the present time.

Between the quasar realm (extending out to distances $\sim$11.5 Glyr) and the nearby galactic nuclei (restricted to distances of a few Mlyr or less), dwell the supermassive black holes accreting at a rate somewhere between the two extremes ($\sim 10\,M_\odot\,yr^{-1}$ in the former case vs $\sim 10^{-2}\,M_\odot$ in the latter case).

We how seem to have a rather good idea of how these objects are distributed around the universe. An important question is which of the central black hole or the surrounding galaxy came first.

Quasars seem to have peaked 10 Gyr ago. On the other hand, light from galaxies originated much later after the universe was 2-4 Gyr older. The most distant quasars seem to be the most energetic ones, so at least some supermassive black holes must have existed near the very beginning. One possibility is that the first supermassive objects formed from a condensation of dark matter alone, and only later these seed black holes have imposed their influence on the baryonic matter. Ordinary matter could not have achieved this early condensation because it wasn't sufficiently clumped to begin with.

The case for a coeval growth of supermassive black holes and galaxies is compelling, specially since a remarkable correspondence between the mass of the black hole and the velocity of stars within the spheroidal component in the host galaxy has been found. Based on the very tight correlation evident, the mass of the central black hole can be predicted with remarkable accuracy by knowing the velocity of stars orbiting very far from it. This is very surprising since the two objects do not directly feel each other through gravitation.

One may hypothesize that once created, a primordial condensation of matter continues to grow with a direct feedback on its surroundings. This may happen either because the quasar heats up its environment and controls the rate at which additional matter can fall in from its neighborhood. Or, because mergers between galaxies affect the growth of colliding black holes in the same way that they determine the energy (thus the average speed) of the surrounding stellar distribution.

Supermassive Black Holes in AGN's;

Astronomers have tended to subdivide active galactic nuclei into groups defined primarily by their specific observational characteristics.

- Seyfert galaxies Constitute one of the largest subgroups of AGN's. These objects tend to be early type spiral galaxies with radio-quiet nuclei. They Can be further divided into two groups; Type 1 and Type 2. The Type 1 display broad and narrow emission lines, while Type 2 predominantly have only the narrow lines. Interpretting the line width as a Doppler effect due to the motion of the emitting gas about the central object, we infer a speed of $\sim 10^4$ km s^{-1} for the broad features, and a much lower speed $< 10^3$ km s^{-1} for the narrow lines. The link between the two subgroups of Seyfert galaxies has been identified as an orientation effect, which is coupled to the geometry of the core. The supermassive black hole is surrounded by a thick molecular torus. Type 1 are oriented such that we can see directly down to the black hole itself, thus exposing the rapidly moving gas. Type 2 are galaxies whose active nucleus contains a torus aligned edge on to the line of sight. This blocks our view of the ionized environment close to the accretor, so we mainly see the narrow lines produced much farther out.

- Quasars are the most luminos members of AGN's. They are spatially unresolved in optical photographs, implying an angular size smaller than ~7". Quasars are themselves subdivi into radio-quiet and radio-loud categories.

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 magnitudes 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.

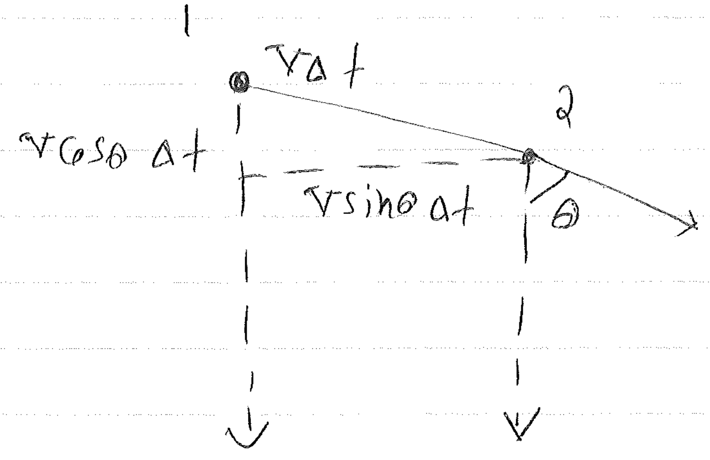
To see this, recall that a time interval $\Delta t'$ in the frame of emitting plasma becomes $\Delta t \sim \gamma^{-1} \Delta t'$ in our frame. Correspondingly, the radiation is blueshifted according to $\nu \sim \gamma \nu'$, and the specific intensity is considerably enhanced

$I_\nu \sim \gamma^3 I'_{\nu'}$. 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 of the jet along the line of sight.



Suppose we observe a blob of relativistic electrons emitting synchrothron radiation as they move from point 1 to point 2 in above figure. The apparent duration of the pulse received on Earth is:

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

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 $\cos\theta_c = \beta$, and reads:

$$v_{max} = \frac{v\sqrt{1-\beta^2}}{1-\beta^2} = \gamma v$$

One can therefore get $v_{max} \gg \gamma v$, even at superluminal values.

An informative survey whose sample includes active galaxies, BL Lac objects, and quasars show that the apparent speeds of jets extend out to 34c. For quasars, the speed is between zero and 10c for most sources.