PHYC 581: High Energy Astrophysics
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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 $E_q \sim L_q t_q \sim 3\times10^{62}$ 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) $M_q \sim 4\times10^{10}\, M_\odot$. 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

$\longrightarrow \frac{GM_q^2}{R} > 10^{65}$ 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 b 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 intergalacti 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). Becaus of their intrinsic brightness, the most distant quasars are see at a time when the universe was a small fraction of its present age. The currend distance record is held by the quasar ULAS J112001.48+064124.3, whic has a redshift $z = 7,085$. 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:

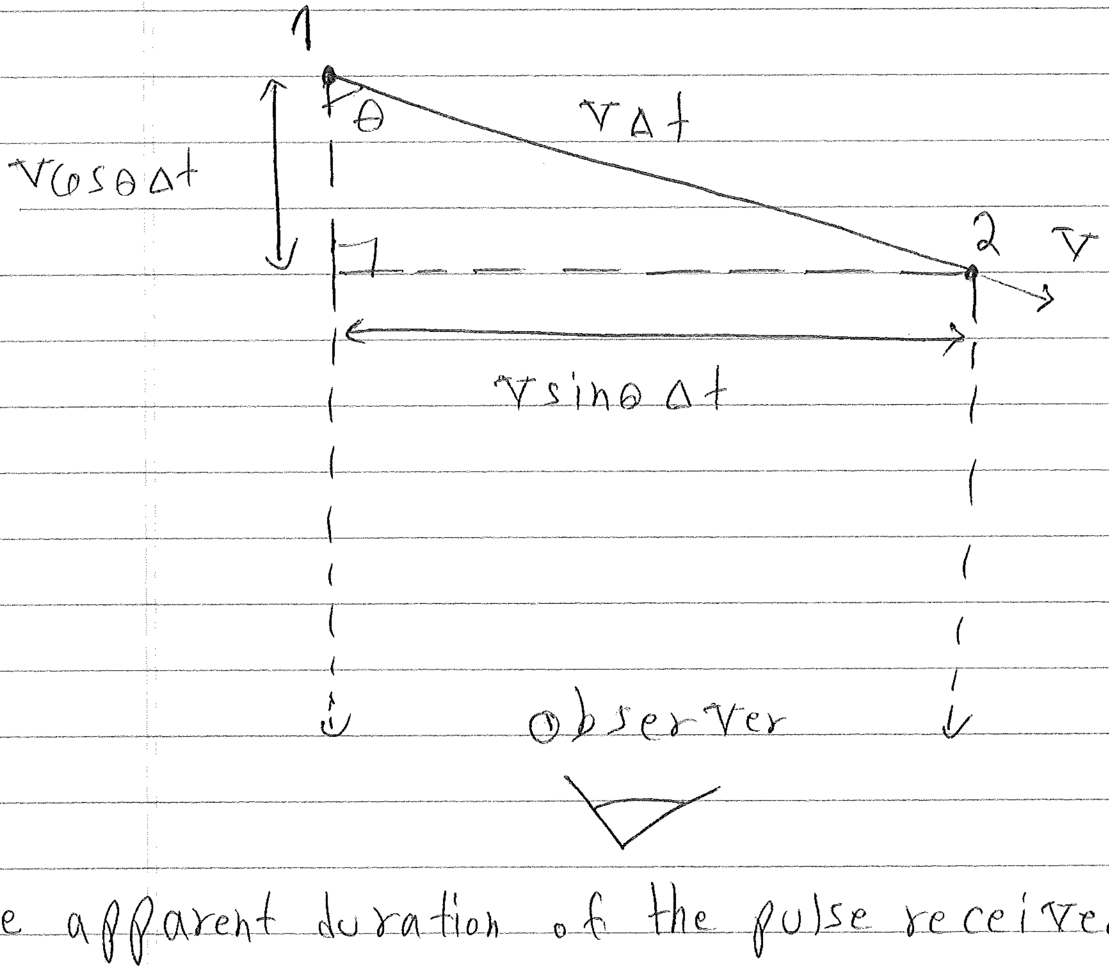
Astronomers have tended to subdivide AGN's into groups defined primarily by their specific observational characteristics. Quasars are the most luminous (and most distant) members of AGN's. They are spatially unresolved in optical photographs, implying an angular size smaller than ~7". Quasars themselves 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 sourc 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:

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

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.

Nearby Objects:

Not all members of the AGN class are necessarily very powerful or very distant. The energy requirements of more abundant low-luminosity objects are less demanding, and long jets or apparent superluminal motion are seen less frequently o or not at all. The evidence for a supermassive black hole is even stronger in these systems due to their proximity. We can study them at a level of detail we cannot even hope to achieve with the others.

(1) The Galactic Center. The material within several parsecs of the nucleus shines in the radio as a three-armed spiral consisting of highly ionized gas radiating a thermal continuum. Each arm is ~3 lyr long. At a distance of 3 lyr from the center the plasma moves at a velocity about 105 kms^{-1}, requiring a mass concentration of ~$3.5 \times 10^6 M_\odot$. The hub of the gas spiral corresponds to the very bright pointlike radio source known as Sagittarius A*, which defines the dynamical center of our galaxy.

X-ray emission has been observed in our galaxy on all scales, from structures extending over kiloparsecs down to a fraction of a light year, with contributions from thermal a non-thermal, pointlike and diffuse sources. The high spatial resolution of the Chandra X-ray observatory allows for a separation of the discrete sources from the diffuse X-ray components pervading the center of our galaxy. A fit to the X-ray emission, assuming optically thin Bremsstrahlung, yields the total inferred mass of $M_{gas} > 0.1 M_{\odot}$ for the emitting gas near Sgr A^*. The hot plasma within a few parsecs of Sgr A^* appears to be injected into the interstellar medium via stellar winds, and the diffuse X-ray emission provides an excellent probe of the gas dynamics near the black hole.

There is ample observational evidence for the existence of strong outflows in and around the nucleus (obtained via the measurement of emission line Doppler shifts). It reveals the presence of 500-1000 $\mathrm{km\,s^{-1}}$ winds and number densities $\sim 10^{3-4}\ \mathrm{cm^{-3}}$ near the mass ejecting stars. The implied total mass injection rate into the galaxy's central region is $\sim (3\text{-}4)\times 10^{-3}\ M_\odot\ \mathrm{yr^{-1}}$. This helps us understand the low average accretion rate $(\sim 10^{-2}\ M_\odot\ \mathrm{yr^{-1}})$ onto black holes at $z \simeq 0$. If the medium

surrounding the central black hole contains little gas, then the accretion cannot grow at rates like those seen at high redshifts. Comprehensive numerical simulations of wind-wind interactions indicate creation of a complex configuration of shocks that efficiently convert the kinetic energy of outflows into internal energy of the gas. The resulting Bremsstrahlung emission produces the entire diffuse X-ray flux detected from the region near Sgr A* by Chandra. It turns out that the outflows bring the environment near the black hole into steady state within $\sim$4,000 years. What we are seeing at the center of our galaxy may be quite typical of nearby galactic nuclei in which the gas content of the central medium has been largely depleted due to black hole accretion and star formation.

(2) M31*. At a distance of 780 kpc, the black hole known as M31* at the nucleus of the Andromeda galaxy is the nearest analog to Sgr A*. The nucleus of Andromea comprises a central dark matter distribution and three concentrations of star light. Two of these have been known for many years. Recent observations with the Hubble Space Telescope have confirmed the existence of a third stellar component. This latter one contains stars with the highest average circular rotation velocity measured so far in any galaxy ($\sim$1,700 $\mathrm{km\,s^{-1}}$).

This implies a mass $\gtrsim 10^8 M_\odot$ for the central object. By using the X-ray emission, and assuming optically thin Bremsstrahlung radiation, one can estimate the temperature and density of the gas, thus the sound speed c_s, near the supermassive black hole. Within the Bondi-Hoyle accretion scenario, and for a typical 10% efficiency for converting accreting mass into radiation, we find a maximum luminosity of $\sim 3 \times 10^{40}$ erg s^{-1} from M31*, whereas the measured X-ray power is about 5 orders of magnitude smaller. This is not unique to M31*, rather it is a common trait among all nearby weak nuclei (including Sgr A*). It is an open question that why the quantity of gas captured does not provide an accurate indication of its emissivity. The possibilities are that either $\dot{M}$ changes with radius (hence not being constant), so that much of the captured matter escapes or is ejected before reaching the region where X-rays are produced, or the radiative efficiency of the plasma is very low.

(3) M 87*. The nucleus of M 87 provides another example of a weak AGN, but its mass is significantly larger than both Sgr A* and M31*. This giant elliptical galaxy contains a black hole of mass $\sim 3 \times 10^{9} M_{\odot}$. The corresponding accretion rate is $\dot{M} \sim 0.1 M_{\odot}\, yr^{-1}$, which translates into a maximal luminosity of $\sim 5 \times 10^{44}$ erg s^{-1} (assuming a 10% efficiency). On the other hand, the implied X-ray power of the central point source is $\sim 7 \times 10^{40}$ erg s^{-1}, which is about four orders of magnitude less than theoretical prediction. However, in case of M 87*, there is a one-sided jet. Most of the radiation in such relativistic outflows appears to

be produced by incoherent Synchrotron and Synchrotron-self-Compton emission in the radio and X-rays/γ-rays respectively. It is straightforward to estimate from the measured luminosity the kinetic power needed to sustain the observed radiative output over its full extent. For M87*, it is $\sim 10^{44}$ erg s^{-1}, which implies the accretion rate matches the overall energetics.