Accretion Disk as Source of Energy and Power in Astrophysical Objects

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ABSTRACT

Energy production in astrophysical objects occurs if materials lose angular momentum by transporting it outwards so that the material can sink lower in the gravitational potential well of the central object. The issue in this theory that is still currently debated relates to the understanding of processes that lead to angular momentum transport and therefore enable mass accretion to occur.

Magneto Rotational Instability (MRI) provides a robust and self-consistent mechanism for the production of turbulence and angular momentum transport in the accretion disks of astrophysical objects if they are adequately ionized, thereby removing the need for ad hoc anomalous viscosity prescription. It has been found that accretion disks of astrophysical objects are adequately ionized. Astrophysical accretion disks are the major source of energy and power in astrophysical objects.

(Key words: accretion disk, cataclysmic variables, angular momentum).

INTRODUCTION

Accretion disks are believed to be the sources of energy in the vicinity of cataclysmic variables (CVs), X-ray binaries, young stellar objects, and the Active Galactic Nuclei (AGN).

Although the Hubble Space Telescope (HST) has imaged AGN disks, it is of binary disks that we have the most detailed knowledge. There are several reasons for this. First, there are large numbers of such systems within 100 pc; such proximity allows fainter spectral features to be analyzed. Second, the primary star in a binary system can sometimes be used as a probe, eclipsing portions of the disk at different times, thereby allowing disk properties to be mapped. Finally, accretion disks in eruptive binary systems are often transitory. The reconstitution of the disk occurs over a time scale convenient for observational monitoring, and much can be learned by studying the evolving spectra.

The discussion on the importance of magnetic stresses maintained by some local dynamo action in producing significant angular momentum transport has been examined by some authors (Eardley and Lightman 1975, Galeev et al. 1979). Perhaps one of the most important and promising developments in recent years, relevant to disks with sufficient ionization and conductivity, has been the application of a hydro magnetic instability in shearing flow, first considered by Vethikov (1959) and Chandrasekhar (1961), to astrophysical accretion disk flows in a series of papers by Balbus and Hawley (1991, 1992a, b) Hawley & Balbus (1992), and Hawley, Gammie & Balbus (1995).

The interest in this instability arises because it is local, strong, and for sufficiently weak fields, depends only on the angular velocity profile in the disk. It also offers the possibility of starting from a simple non-turbulent disk flow with a simple magnetic field configuration and calculating the angular momentum transport resulting from the fully developed turbulence produced by instability.

What is hydro magnetic instability? If we consider an outwardly displaced fluid element in a differentially rotating disk threaded by a vertical magnetic field; the fundamental point is that the element is elastically tethered by a vertical magnetic field, which is trying simultaneously to enforce rigid rotation (by resisting shearing), and to return the element back to its starting point (by resisting stretching).

The latter is clearly stabilizing but the former is the heart of the instability; the field is trying to force the element to rotate too fast for its new radial location. The excess centrifugal force drives the element still further outward. At long wavelengths, the return force is weak and the result is the instability. The growth rate of this instability, which is of the order of the disk angular frequency, is considerably more rapid than any wave propagation time of interest (Balbus and Hawley 1991).

The discovery of the relevance of the Magneto Rotational Instability (MRI) (Balbus and Hawley 1991) has opened up a new era in accretion disk astrophysics. The instability provides a robust and self-consistent mechanism for the production of turbulence and angular momentum transport in these objects if they are adequately ionized, thereby removing the need for ad hoc anomalous viscosity prescription (Steinaker and Papaloizou 2002). Further still, toroidal field buildup enables mass to accrete through it onto the central star, through the operation of magnetic torques (Steinaker and Papaloizou 2002). Although magnetic activity (Galeer et al. 1979, Rozyczka et al. 1996) has not been directly observed in the disks, it has been inferred (Horne 1994) from the apparent correlation between the emission line surface brightness and orbital rotation frequency (Horne and Saar 1991). This correlation is in close agreement with that found for calcium, hydrogen, and potassium lines in stars and in the quiet regions on the solar surface (Schrijver 1987, 1992).

Spectroscopic study, especially in the extreme ultraviolet (EUV) range of CVs, provides one of the best astrophysical laboratories for the study of accretion physics (Craig et al 1997). Eze and Okeke (2004) used the EUV spectral lines to study accretion disks of CVs and were able to identify a number of spectral emission lines from the CVs and suggested that the accretion disks of these CVs were adequately ionized. This implies that the accretion disks of other astrophysical objects could equally be adequately ionized. This result is in agreement with the suggestion that the most promising candidate for providing angular momentum transport mechanism during the outburst is Magneto Rotational Instability.

The extraction of gravitational potential energy from materials, which accretes on to a gravitating body, is now known to be the principal source of power in several types of close binary systems and is widely believed to provide the power supply in active galactic nuclei and quasars. This increasing recognition of the importance of accretion has accompanied the dramatic expansion of observational techniques in astronomy, in particular the exploitation of full range of the electromagnetic spectrum from the radio to X-rays and γ-rays. The accretion disks, especially in X-ray binaries, are the most efficient machines for extracting gravitational potential energy and converting it into radiation (Frank et al. 1992). This property of accretion disks has been suggested as the power source of the central engine in quasars and active galactic nuclei. The disk-like accretion onto a black hole is the most plausible explanation for the strong emission in the ultraviolet (UV), the so-called "big blue bump" (Shields 1978) and for the X-rays in AGN.

Relativistic jets can extract high amounts of energy from a central object (Falcke and Biermann, 1995). Pudritz (1986) proposed that a magnetohydrodynamic (MHD) jet could extract angular momentum of the accretion process in the vicinity of the accretion disk, so that the jet can control the accretion process in the vicinity of the last marginally stable orbit. The conservation laws of mass, angular momentum, and energy govern the jet disk system.

Energy production occurs if material can lose angular momentum by transporting it outwards, so that it can sink lower in the gravitational potential of the central object. In this way the accretion process provides a power source for astrophysical objects. Clearly, an important issue in the theory of accretion disks is the understanding the of processes that lead to outward angular momentum transport and therefore enable mass accretion to occur.

Some simple order of magnitude estimates (Frank et al. 1992) show that for a body of mass (M) and radius (R*) the gravitational potential energy released by the accretion of a mass (m) onto its surface is:

$$\Delta E_{acc} = GMm/R_* \quad \text{..........} \quad \textbf{(1.1)}$$

where G is the gravitation constant. If the accreting body is a neutron star with radius R* - 10km, mass $M \sim M_\odot$, the solar mass, then the yield ΔE_{acc} in about 10^{20} erg per accreted gram. We would expect this energy to be electromagnetic radiation. For comparison, consider the energy that could be extracted from the same mass by nuclear fusion reactions. The maximum is obtained if, as is usually the case in astrophysics, the material is hydrogen, and the major contribution comes from the conversion, (or "burning"), of hydrogen to helium. This yields an energy release as follows:

$$\Delta E_{nuc} = 0.007\, mc^2 \quad \textbf{(1.2)}$$

where c is the speed of light, so we obtain about 6 x10^{18} erg or about one twentieth of the accretion yield in this case.

We can state from equation (1.1) that the efficiency of accretion as an energy release mechanism is strongly dependent on the compactness of the accreting object: the larger the ratio M/R*, the greater the efficiency. Thus, in treating accretion on to objects of stellar mass we shall certainly want to consider neutron stars (R* = 10km) and black holes with radii R*

$$\sim 2G \, {}^{M}\!/_{c^2} \sim 3\left({}^{m}\!/_{M_o}\right) km \quad \textbf{(1.3)}$$

For white dwarfs with M~M⊙, R*~10^9 cm, nuclear burning is more efficient than accretion by factors 25-50. However, it would be wrong to conclude that accretion onto white dwarfs is of no great importance for observations, since the argument takes no account of the timescale over which the nuclear and accretion processes act. In fact, when nuclear burning does occur on the surface of a white dwarf, it is likely that the reaction tends to run away to produce an event of great brightness but short duration; a nova outburst, in which the available nuclear fuel is very rapidly exhausted. For almost all its lifetime no nuclear burning occurs, and the white dwarf (may) derive its entire luminosity from accretion.

THE BASIC MODEL OF ACCRETION DISK IN CATACLYSMIC VARIABLES

The basic and most popular model in the accretion disk processes in binary system is the Roche lobe overflows model (Frank et al. 1992). In this model, one of the stars fills its Roche lobe by either expansion or the binary separation shrink, to the point where the gravitational pull of the companion can remove the outer layers of its envelope (Roche lobe overflow) and starts transferring material to its companion (Figure 1).

Usually, the secondary star is a late type star (e.g. red giant or even main sequence star), while the primary star is a white dwarf, neutron star, or even a black hole. The nature of the primary star can be determined through the temperature of the emergent spectrum. The lower the temperature, that is the softer the X-rays spectrum, the lower the M/R ratio. White dwarfs would have M/R ≈ 10^2, neutron stars and black holes would have M/R ≥ 10^5, so that in general, the more collapsed the primary star the higher the temperature and luminosity (Shore 1988).

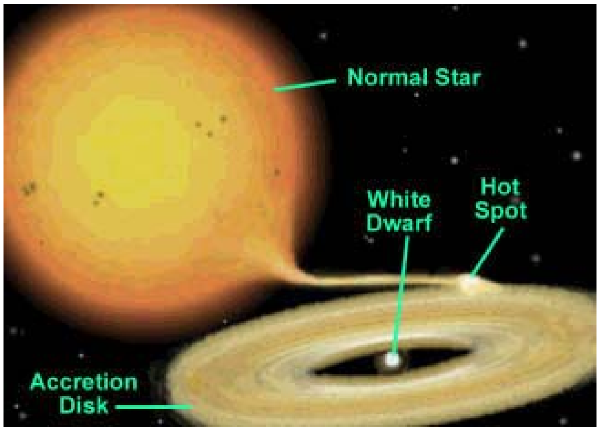

Figure 1: An Artist's Rendition of the Structure of a CV (Adapted with permission from http://heasarc.gsfc.nasa.gov/Images/exosat)

In a binary system with the secondary star filling the Roche lobe and transferring mass into the lobe of the compact primary, the transferred material has too much angular momentum to fall directly on to the surface of the white dwarf, but instead builds an accretion disk, which spirals round the while dwarf. The matter in the disk will be accreted onto the white dwarf if it losses its angular momentum. The matter in the disk losses its angular momentum gradually and moves toward the accreting star.

The angular momentum transport in the disk has been a major source of debate in the last decade. Why does the angular momentum loss lead to accretion of matter onto the while dwarf? If we consider a projected particle to be in a circular orbit around a central gravitating body the particle will stay in the orbit just like artificial satellites in the earth's orbit. If, however, there is an existing process that can extract energy and angular momentum from the particle, the particle will spiral inwards. It has been suggested that the amount of energy that can be extracted by such a process is equal to the binding energy of the innermost orbit (Pringle 1981). This implies that the accretion process can be an efficient converter of rest mass energy to radiation energy. A problem with this theory rests in the nature of the process for extraction of such energy and angular momentum from the accretion disk. This, we will discuss in subsequent sections.

In a few of the binary stars (CVs) the primary star is strongly magnetic (B ≈ 10^7 – 10^8 G) and the accreting matter is funneled radially onto the magnetic poles.

THE STRUCTURE OF THE ACCRETION DISK IN NEUTRON STARS

If the star has a companion, it can accrete from the companion. If the companion is a low-mass star, say half the mass of our Sun or lower, accretion tends to proceed by Roche lobe overflow. This type of flow has a lot of angular momentum, so the matter forms a disk around the star (Figure 2).

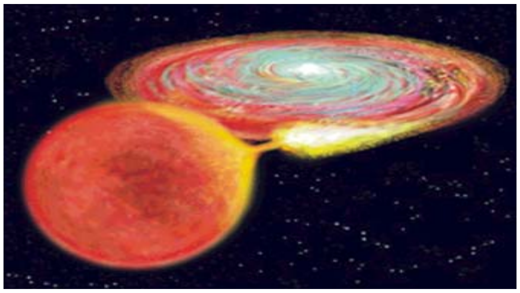

Figure 2: An Artist's Rendition of a how a Neutron Star Accretes Material form its Stellar Companion via Roche Lobe Overflow
(Adapted with permission from http://universe.gsfc.nasa.gov/resource/glossary.html#neutron Star)

The radius of the inner edge of the disk is determined by the strength of the magnetic field. The stronger the field, the farther out it can control the accretion flow (for a given accretion rate). The star then (more or less) tries to come to equilibrium with the Keplerian angular velocity of the matter at the inner edge of the accretion disk. This means that neutron stars with relatively small (10^8 to 10^9 Gauss) magnetic fields can be spun up to high frequencies, and this is the accepted picture of how we get millisecond pulsars.

If the companion of the neutron star is a high-mass star (over 10 solar masses), then the matter that makes it onto the neutron star progresses in the form of a low angular momentum wind. Therefore, the neutron star will not be spun up to such high frequencies; in fact, some pulsars that are in high-mass systems have periods longer than 1000 seconds. The process of wind accretion is a very complicated one, and numerical simulations of the process push the limits of today's computers. It appears that, in some circumstances that a disk may form briefly around the neutron star, only to be dissipated and replaced by a disk going the other way.

If part of the companion star's envelope is close enough to the neutron star, the neutron star's gravitational attraction on that part of the envelope is greater than the companion star's attraction, with the result that the gas in the envelope falls onto the neutron star (Figure 3). However, since the neutron star is tiny, astronomically speaking, the gas has too much angular momentum to fall on the star directly, and therefore orbits around the star in an accretion disk. Within the disk, magnetic or viscous forces operate to allow the gas in the disk to drift in slowly as it orbits, and to eventually reach the stellar surface. If the magnetic field at the neutron star's surface exceeds about 10^8 G, then before the gas gets to the stellar surface, the field can couple strongly to the matter and force it to flow along field lines to the magnetic poles. The friction of the gas with itself as it spirals in towards the neutron star heats the gas to millions of degrees, and causes it to emit X-rays.

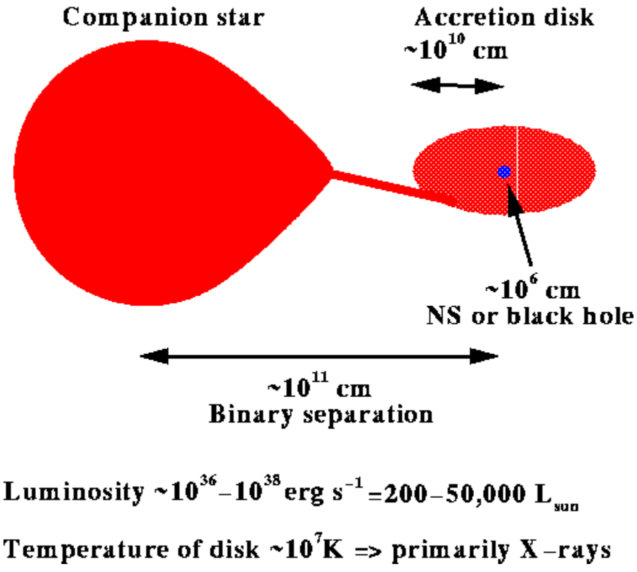

Figure 3: Accreting Neutron Star or Black Hole
(Adapted with permission from http://*wwwastro.msfc.nasa.gov/xray/openhous/ns/*)

Some characteristic dimensions of this sort of system are displayed in Figure 4. Neutron stars in this kind of system are believed to have surface magnetic fields between 10^7 and 10^{10} Gauss. This means that the accreting gas can spiral very close to the neutron star before it is grabbed by the magnetic field. At such a close distance, the orbital frequency is very high (hundreds of Hertz), so the neutron star is spun up rapidly. As mentioned earlier, this is how many researchers believe millisecond pulsars arise. Those millisecond pulsars are extremely stable rotators; the best are at least as stable as atomic clocks. There have been suggestions that using millisecond pulsars as cosmic clocks could tell us about all sorts of exotic things, such as the presence of a background of gravitational radiation left over from the Big Bang.

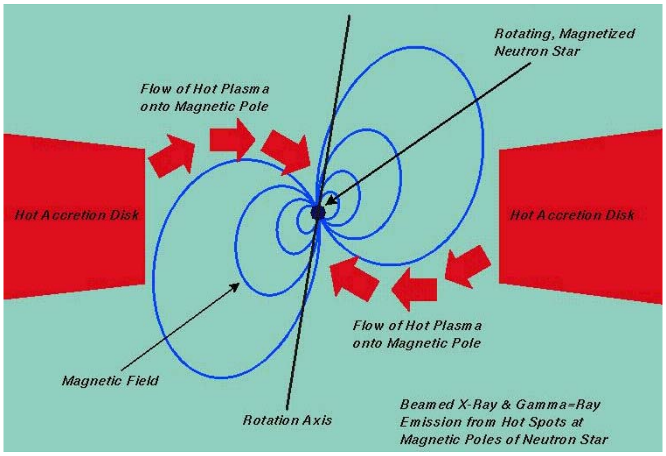

Figure 4: An Illustration of the Inner Region where the Neutron Star's Magnetic Field Controls Matter (Adapted with permission from http://*wwwastro.msfc.nasa.gov/xray/openhous/ns/*)

Another phenomenon associated with neutron stars that have low-mass companions is X-ray bursts. These typically last a few seconds to a few minutes, and have peak luminosity nearly a hundred thousand times our Sun's luminosity. The model for these bursts is that as hydrogen and helium are transferred to the neutron star from the companion, it builds up in a dense layer. Eventually, the hydrogen and helium have been packed in a layer so dense and hot that thermonuclear fusion starts, which then converts most or all of the gas into iron, releasing a tremendous amount of energy. This is the equivalent of detonating the entire world's nuclear arsenal on every square centimeter of the neutron star's surface within a minute!

If the companion to the neutron star has a mass between one and ten times our Sun's mass, the mass transfer is unstable and does not last very long, so there are few objects in this category.

If the companion to the neutron star has a mass more than about ten times our Sun's mass, the companion naturally produces a stellar wind, and some of that wind falls on the neutron star. The neutron stars in these systems have strong magnetic fields, around 10^{12} Gauss (similar to typical isolated pulsars). At field strengths this high, almost all the accreting gas is forced to flow along field lines to the magnetic poles. This means that the x-rays primarily come from the resulting hot spots on the poles. It also means that if the magnetic and rotation axes of the star are not co-aligned, the radiation sweeps past once per rotation and we see x-ray pulsation. These systems are therefore called "accretion-powered pulsars"; to distinguish them from the "rotation-powered pulsars" that Jocelyn Bell discovered.

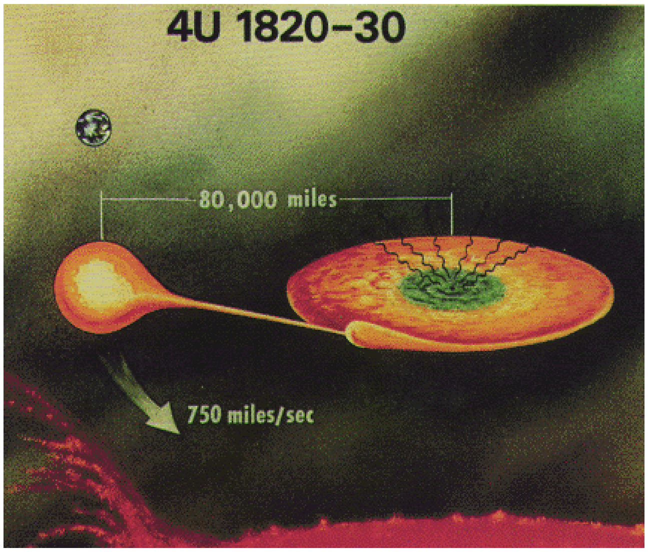

Figure 5: An Artist's Rendition of 4U~1820-30, which has a Binary Period of Just over Eleven Minutes (Adapted with permission from http://heasrc.gsfc.nasa.gov/Images/exosat/slide_gifs/exostat18.gif)

BLACK HOLES

Black holes are objects so dense that not even light can escape their gravity, and since nothing can travel faster than light, nothing can escape from inside a black hole. A black hole can be thought of as any star compressed so greatly that it not only has a photon sphere but also an event horizon (Figure 5). On the other hand, a black hole exerts the same force on something far away from it as any other object of the same mass would. For example, if our Sun was magically crushed until it was about 1 mile in size, it would become a black hole, but the Earth would remain in its same orbit.

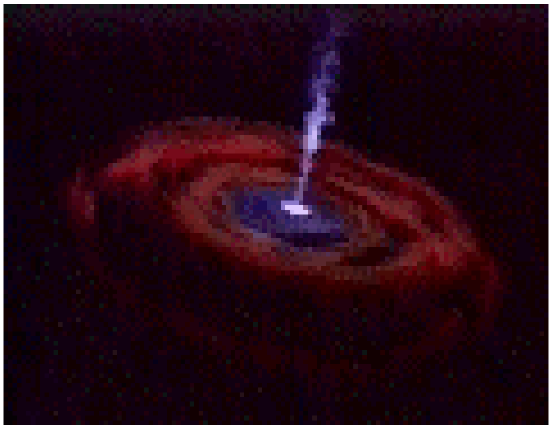

Figure 6: An Artist's Rendition of a Black Hole
(Adapted with permission from http://heasrc.gsfc.nasa.gov/)

Even back in Isaac Newton's time, scientists speculated that such objects could exist; even though we now know they are more accurately described using Einstein's General Theory of Relativity. Using this theory, black holes are fascinating objects where space and time become so warped that time practically stops in the vicinity of a black hole.

Contrary to popular belief, there is a great deal of observational evidence for the existence of two types of black holes; those with masses of a typical star, and those with masses of a typical galaxy. The former type has measured masses ranging from 4 to 15 Suns, and is believed to be formed during supernova explosion. The after-effects are observed in some X-ray Binaries known as black hole candidates.

On the other hand, galaxy-mass black holes are found in AGN. These are thought to have the mass of about 10 to 100 billion Suns. The mass of one of these *super massive black holes* has recently been measured using radio astronomy. X-ray observations of iron in the accretion disk may actually be showing the effects of such a massive black hole as well.

ACCRETION DISKS IN AGN

Some galaxies exhibit intense nuclear activity with luminosity reaching 10^{47}ergs^{-1} (Schmidt and Green 1983, Osterbrock 1989). If AGN represent a generic phase in galactic evolution, their abundance relative to spiral galaxies would suggest that they might persist for 10^{8}y^{-1}(Woltjer 1959).

During this phase the amount of energy radiated is comparable to the rest mass energy of the residual gas observed in typical galaxies today (Sanders et al 1988). The energy source of AGN is based on accretion onto massive black holes (MBHS) (Lynden – Bell 1969). The images and spectra obtained with the Hubble Space Telescope provide direct evidence for a rotating gaseous disk, on the scale ~ 20pc, around the nucleus of M87 (Ford et al. 1984). The existence of accretion disks has also been inferred from the radiation characteristics of AGN. For example, the observed excess in the blue and UV continuum (with $\lambda \sim 1 - 4 \times 10^{3}$ Å) has been interpreted as radiation emerging from disks on the scale ~ 10^{2} to 1pc (Shields 1978, Malkan & Sargent 1982, Sanders et al. 1989).

The minimum mass accretion rate $\dot{M}$ ~1M$_\odot$ y^{-1} is inferred for most luminous (~10 L$_\odot$) sources, based on the assumption that all the rest mass energy of the accreted matter is converted into radiation (Lin and Papaloizou 1996). Larger values of $\dot{M}$ are required for modest or low conversion efficiency. If the emergent luminosity does not exceed the Eddingaton limit (Sun and Malkan 1989) such large accretion rates are only possible if the MBH has a mass $M_{bh} > 10^{8}$ - 10^{9}M$_\odot$. This mass is comparable to the dynamic mass required to account for the rotation velocity of the gas at the center of M87 (Ford et al. 1984) and the profile of broad emission lines shaped by the effect of Doppler broadening (Netzer 1990). The observed X-ray luminosity of NGC4258 is $\times 10^{40}$ergs^{-1} (Makisima et al. 1994) if this luminosity is powered by accretion onto the MBH with 1% efficiency.

DISCUSSIONS AND CONCLUSIONS

The central problem of nearly 30 years of accretion disk theory has been how to understand the process by which they accrete (that is how materials are transferred from the accretion disk to the accreting object). In principle, the presence of friction in the form of viscosity allows the exchange of angular momentum between adjacent fluid elements, but this fails to account for the observed accretion rates. If on the other hand, the disk were turbulent, the effective viscosity could be large enough to provide the needed accretion rates. Magneto Rotational Instability provides a robust and self-consistent mechanism for the production of turbulence and angular momentum in these objects if they are adequately ionized (Steinaker and Papaloizou 2002).

Young Stellar Objectives

In Young Stellar Objects (YSOs), it is well believed that the torque exerted upon disks by centrifugal driven winds cannot account for both the observed linear momentum and energy transport rates associated with the molecular out flows (Pudritz and Norman 1986). It is our view that the luminosity associated with proto-stellar objects during the molecular outflows epoch is due to accretion from the disk. This implies that molecular outflows in the form of jets in the Young Stellar Objects are originally powered by the gravitational potential energy liberated by matter accreting from the accretion disk onto a forming star.

Active Galactic Nuclei

The energy source of AGN is from accretion of matter from the accretion disk onto the massive black hole. Tremendous amounts of energy are released in the form of radiation when a mass (m) is accreted onto a massive black hole.

It is our theory that the initial injection of matter in the AGN jets is powered by the gravitational potential energy released as result of accretion of matter onto the massive black hole.

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