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STAR FORMATION NEAR SUPERMASSIVE BLACK HOLES

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RESUMEN

La acreción de los agujeros negros supermasivos y la formación estelar parecen estar íntimamente relacionados. Evalúo la evidencia teórica y observable de esta afirmación y expongo cómo estudios específicos de dos sistemas, nuestro Centro Galáctico y el núcleo de M87, pueden ayudarnos a comprender mejor estos procesos.

ABSTRACT

Supermassive black hole accretion and star formation appear intimately connected. I review the observational and theoretical evidence for this statement. I then discuss how focussed studies of two systems, our Galactic Center and the nucleus of M87, can help to improve our understanding of these processes.

Key Words: **ACCRETION, ACCRETION DISKS — GALAXIES: ACTIVE — STARS: FORMATION**

1. OBSERVATIONAL EVIDENCE

Young, massive stars are seen within 0.5 pc of Sgr A* in our Galactic center (Lu et al. 2005; Eisenhauer et al. 2005). How they formed there is considered in §3. An A-star spectrum, indicating relatively young stars, is observed in M31's nucleus (Bender et al. 2005). Late-type disk galaxies often have massive nuclear star clusters (Walcher et al. 2005), although it is usually difficult to tell if supermassive black holes are also present. In earlier-type galaxies the black hole mass is $\sim$0.6% of the spheroid stellar mass (Magorrian et al. 1998), indicating that star formation has proceeded in step with black hole growth. When we see black holes growing, i.e. as quasars, there is often an IR bump in their spectra (Elvis et al. 1994), which could be due to star formation (Sirko & Goodman 2003). Quasar spectra also show that gas near the black hole has high metallicity (Hamann et al. 2002), presumably because of massive star formation. Star formation is observed in the nuclei of Seyfert galaxies (Terlevich 1996). In luminous IR galaxies (LIRGs) large amounts of gas are driven into the nuclei and star formation produces much of the luminosity (Alonso-Herrero et al. 2006). Ultra-luminous IR galaxies (ULIRGs) are more extreme examples of such systems, containing massive circumnuclear disks of molecular gas thought to be self-regulated against gravitational collapse by star formation (Downes & Solomon 1998). Radio supernovae have been observed in the nuclei of ULIRG Arp 220, occurring at a rate of at least 4 per year (Lonsdale et al. 2006).

2. THEORETICAL EXPECTATION

If a gas disk has a high enough surface density, Σ, and is sufficiently cool (i.e. if the effective sound speed, c_s, is small enough), then it will be gravitationally unstable. The Toomre parameter describing this condition for a Keplerian disk is

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} = \frac{3\alpha c_s^3}{G\dot{M}} = 0.71\alpha \frac{c^3_{s,10\ \mathrm{km\ s^{-1}}}}{\dot{M}_{M_\odot\ \mathrm{yr}^{-1}}}, \quad (1)$$

where instability occurs for $Q < 1$. Here we substituted Σ for the mass accretion rate, $\dot{M} = 3\pi\nu\Sigma$ of a disk with viscosity $\nu = \alpha c_s h$ and scaleheight h (Goodman 2003). The Shakura-Sunyaev viscosity parameter α takes values of about unity in self-gravitating disks. Gammie (2001) finds $\alpha \simeq 0.3$ from 2D simulations of local patches of a disk. Global simulations of disks around massive protostars indicate that the effective viscosity due to spiral density waves is about an order of magnitude larger than this (M. Krumholz, priv. comm.). If the over-dense regions created by gravitational instability have a high enough cooling rate, they should fragment into stars.

The surface temperature of an optically thick disk heated solely by viscous dissipation scales as $r^{-3/4}$ and the central temperature falls off at a similar or even faster rate depending on the energy transport mechanisms operating in the disk and the opacity of the gas. For example for constant opacity and radiative diffusion, the midplane temperature falls as $r^{-9/10}$ and so, for thermal pressure support, the effective sound speed scales as $c_s \propto r^{-9/20}$. For a typical quasar with $M = 10^8\ M_\odot$ accreting at the Eddington rate, the radius at which Q drops to unity is $\sim 10^{-2}$ pc (Goodman 2003). Viscous dissipation

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can only stabilize the very inner regions of these accretion disks. In the scenario we consider to be most likely for Galactic center star formation (§3), viscous dissipation is relatively more important since the young stars are forming very close to the black hole. In the sub-Eddington, ~ 100 pc disk of M87 (§4), heating due to viscous dissipation is much too small to stabilize the disk (Tan & Blackman 2005).

A number of additional factors may enhance disk stability. The outer disk may be heated by radiation liberated in the inner disk close to the black hole, although in practice this is not a very significant effect (Goodman 2003). The basic problem is that little of the flux from the central source will be intercepted by a geometrically thin disk. If the equatorial region and disk are also optically thick, then the flux will tend to be beamed out in the polar directions.

The disk will also be heated by the general radiation field present at the center of its galaxy. Levin (2006) considered this for our Galactic center, using a luminosity from young stars in the inner $\sim$ pc of $\sim 10^7\ L_\odot$ and concluding the disk would be heated to about 80 K, which dominates viscous heating beyond $\sim$0.06 pc. However, the luminosity from young stars is expected to show temporal fluctuations depending on the recent star formation activity. In the center of an elliptical galaxy the main sources of irradiation are the older stellar population and x-rays from the hot interstellar medium (ISM).

In the local Galactic ISM, thermal pressure is not the dominant component of support and magnetic fields, with pressure $P_B \propto B^2$, play a significant role (Heiles & Crutcher 2005). This may also be true in circumnuclear disks. If magnetic flux, B, is frozen into the gas, then $P_B \propto \Sigma^2$, which is enough to compensate for the increasing weight of the gas $P_G \simeq G\Sigma^2$ in a compressed region. For fragmentation and star formation to be able to occur in a disk in which magnetic fields are important for stability on large scales, we expect that magnetic flux must diffuse out of the over-dense regions. If the field cannot diffuse significantly, this is equivalent to a small effective cooling rate for the gas. Magnetic field will tend to diffuse out of dense gas, either by ambipolar or turbulent diffusion. We expect that relatively strong magnetic fields will act to slow the rate of star formation in a globally unstable disk, but will be unlikely to prevent it completely.

Thus, the theoretical expectation is that circumnuclear disks are gravitationally unstable, except in their very central regions, and so form stars. Star formation helps to stabilize a disk by both consuming gas, which reduces Σ, and heating the remainder, which raises c_s. Tan & Blackman (2005) considered these two effects in the context of Bondi-fed accretion disks around the supermassive black holes in giant elliptical galaxies. Thompson, Quataert, & Norman (2005) modeled the stability of disks with higher accretion rates, applicable to quasar and ULIRG systems. In both cases, for disks that self-regulate to $Q = 1$, most of the mass flux being fed to the disk at its outer edge turns into stars.

The above models must assume a heating rate per mass of stars formed, which depends on their initial mass function (IMF). Conditions in the outer parts of circumnuclear disks are not expected to be that different from typical Galactic star-forming regions, with the exception of somewhat higher ambient temperatures and pressures. The Bonnor-Ebert mass, which is the maximum mass of a stable isothermal sphere of gas and may be related to the peak of the stellar IMF, scales as $T^2P^{-1/2}$, so the higher temperatures and pressures of circumnuclear disks tend to counteract each other in this regard.

The disk orbital time scales as $t_{\rm orbit} \propto r^{3/2}$ while the local star formation time for a fixed stellar mass (McKee & Tan 2003) scales as $t_{*f} \propto P^{-3/8} \propto \Sigma^{-3/4} \propto r^{9/8}$, where the last proportionality assumes the structure of a constant Q disk with viscosity proportional to total pressure (Goodman 2003). We expect $t_{*f} \ll t_{\rm orbit}$ in the outer disk, but these may become comparable to each other in the inner regions. In this case, the collapsing fragment is likely to gain significant mass by sweeping up gas from the disk in a runaway process only halted once a gap is opened up. In quasar accretion disks this process may lead to supermassive stars (Goodman & Tan 2004), while in the Galactic center (Nayakshin 2006a) it may help to explain the IMF, which is observed to be top-heavy (Nayakshin et al. 2006b).

3. THE GALACTIC CENTER

The distribution of many of the young stars near Sgr A* in a disk-like system and the lack of a larger-scale distribution suggests formation *in situ*, rather than inspiral as part of a cluster. Star formation in this region does not appear to be active today, so we can view this process as episodic, with the last burst occurring about 5-10 Myr ago. Dense, probably bound, molecular gas clumps are observed within a few pc of Sgr A* (Herrnstein & Ho 2005; Christopher et al. 2005). The scenario we envisage to explain the recent Galactic center star formation is the infall of such a clump after having its orbit perturbed by either a cloud collision or interaction with a supernova explosion. As the clump approaches the black hole, it is tidally disrupted. Some of the gas is shocked and then cools to form a disk or ring.

As an example of this process, consider a clump with $2 \times 10^4\ M_\odot$ that is able to feed half its mass into a disk with radial size of 1 pc, so that $\bar{\Sigma} = 0.66\,\mathrm{g\,cm^{-2}}$. Assume the gas disk can cool to an effective temperature of 100 K (lower temperatures are hard to achieve given the local stellar radiation field) with effective sound speed of $0.6\ \mathrm{km\,s^{-1}}$. Evaluating the Toomre parameter we find

$$Q \equiv 2.0 c_{s,\mathrm{km\,s^{-1}}} \frac{M^{1/2}_{\mathrm{BH},4\times10^6\,\mathrm{M}_\odot}}{r^{3/2}_{\mathrm{pc}} \Sigma_{\mathrm{g\,cm^{-2}}}}, \qquad (2)$$

and the disk would be close to the threshold of instability. However, this simple analysis does not allow for the fact that, if the viscosity is relatively low, the gas will tend to pile up at the outer edge of the disk, forming a ring with a much higher surface density. Numerical simulations, that adequately resolve the formation of a circumnuclear disk and the star formation process within it, are required in order to investigate this scenario in more detail.

4. BONDI-FED DISKS IN ELLIPTICALS: M87

The black holes in the centers of giant elliptical galaxies should accrete interstellar gas by Bondi accretion, and this expected accretion rate can be inferred from x-ray observations of the density and temperature of the gas in nearby systems like M87 (Di Matteo et al. 2003). With this constraint on the mass supply rate to the disk, such systems present special opportunities for testing models of disk accretion, possible star formation and black hole fueling.

Tan & Blackman (2005) considered the gravitational stability of the accretion disk in M87, which is ~100 pc in radial extent and thought to be fed at $\sim 0.04 - 0.15\ M_\odot\ \mathrm{yr}^{-1}$. They predicted the disk should be unstable and form stars. A simple model for self-regulation ($Q \simeq 1$) of the disk by star formation led to the prediction of a cold molecular gas mass of $1 - 5 \times 10^6\ M_\odot$. Observations of CO(J=2-1) with the Sub-MM Array yield mass estimates of $4.3 \pm 1.2 \times 10^6\ M_\odot$ in agreement with this prediction (Tan et al. 2006), although higher sensitivity data are required for definitive confirmation.

Additional predictions of the model are thermal emission from dust in this gas and emission from young stars forming at $\sim 0.01 - 0.1\ M_\odot\ \mathrm{yr}^{-1}$. Perlman, Mason, Packham et al. (2007, these proceedings) reported a 60 K thermal component in the nucleus with luminosity $4 \times 10^{38}\ \mathrm{ergs\,s^{-1}}$. This is much smaller (by factors of $\sim 10^3$) than the luminosity expected from the above star formation rates, but more luminosity may be being released from cooler dust that is not probed by the 35 μm longest wavelength of the Perlman et al. observations. The Hα luminosity of the M87 disk is consistent with the above star formation rate (Tan & Blackman 2005), although it is difficult to assess how much of this is due to ionization by the AGN (Kim, Ho, & Im 2006).

The M87 nucleus is underluminous by a factor of ~100 compared to models of thin disk accretion at the Bondi rate. It is possible that star formation, by acting as a mass sink, helps to explain this discrepancy (Tan & Blackman 2005). It is also possible that in the central regions of the disk there is a transition to a radiatively inefficient accretion flow.

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