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Abstract: Disk galaxies at high redshift have been predicted to maintain high gas surface densities due to continuous feeding by intense cold streams leading to violent gravitational instability, transient features, and giant clumps. Gravitational torques between the perturbations drive angular momentum out and mass in, and the inflow provides the energy for keeping strong turbulence. We use analytic estimates of the inflow for a self-regulated unstable disk at a Toomre stability parameter $Q < 1$, and isolated galaxy simulations capable of resolving the nuclear inflow down to the central parsec. We predict an average inflow rate $10 M$ sun yr$^{-1}$ through the disk of a $10^{11}$ M sun galaxy, with conditions representative of $z = 2$ stream-fed disks. The inflow rate scales with disk mass and $(1 + z)^{3/2}$. It includes clump migration and inflow of the smoother component, valid even if clumps disrupt. This inflow grows the bulge, while only a fraction of $> 10^{-3}$ of it needs to accrete onto a central black hole (BH), in order to obey the observed BH-bulge relation. A galaxy of $10^{11}$ M sun at $z = 2$ is expected to host a BH of $108 M$ sun, accreting on average with moderate sub-Eddington luminosity $L_X \sim 10^{42}-10^{43}$ erg s$^{-1}$, accompanied by brighter episodes when dense clumps coalesce. We note that in rare massive galaxies at $z = 6$, the same process may feed $10^9$ M sun BH at the Eddington rate. High central gas column densities can severely obscure active galactic nuclei in high-redshift disks, possibly hindering their detection in deep X-ray surveys.

DOI: [https://doi.org/10.1088/2041-8205/741/2/L33](https://doi.org/10.1088/2041-8205/741/2/L33)

Other titles: Black Hole growth and AGN obscuration by instability-driven inflows in high-redshift disk galaxies fed by cold streams

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ZORA URL: [https://doi.org/10.5167/uzh-54772](https://doi.org/10.5167/uzh-54772)

Journal Article

Published Version

Originally published at:
Bournaud, F; Dekel, A; Teyssier, R; Cacciato, M; Daddi, E; Juneau, S; Shankar, F (2011). Black hole growth and active galactic nuclei obscuration by instability-driven inflows in high-redshift disk galaxies fed by cold streams. *Astrophysical Journal Letters*, 741(2):L33.

DOI: [https://doi.org/10.1088/2041-8205/741/2/L33](https://doi.org/10.1088/2041-8205/741/2/L33)
BLACK HOLE GROWTH AND ACTIVE GALACTIC NUCLEI OBSCURATION BY INSTABILITY-DRIVEN INFLOWS IN HIGH-REDSHIFT DISK GALAXIES FED BY COLD STREAMS

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Received 2011 July 7; accepted 2011 September 20; published 2011 October 20

ABSTRACT

Disk galaxies at high redshift have been predicted to maintain high gas surface densities due to continuous feeding by intense cold streams leading to violent gravitational instability, transient features, and giant clumps. Gravitational torques between the perturbations drive angular momentum out and mass in, and the inflow provides the energy for keeping strong turbulence. We use analytic estimates of the inflow for a self-regulated unstable disk at a Toomre stability parameter \( Q \sim 1 \), and isolated galaxy simulations capable of resolving the nuclear inflow down to the central parsec. We predict an average inflow rate \( \sim 10 M_\odot \text{yr}^{-1} \) through the disk of a \( 10^{11} M_\odot \) galaxy, with conditions representative of \( z \sim 2 \) stream-fed disks. The inflow rate scales with disk mass and \((1 + z)^{3/2}\). It includes clump migration and inflow of the smoother component, valid even if clumps disrupt. This inflow grows the bulge, while only a fraction of \( > 10^{-3} \) of it needs to accrete onto a central black hole (BH), in order to obey the observed BH–bulge relation. A galaxy of \( 10^{11} M_\odot \) at \( z = 2 \) is expected to host a BH of \( \sim 10^8 M_\odot \), accreting on average with moderate sub-Eddington luminosity \( L_X \sim 10^{42}–10^{43} \text{erg s}^{-1} \), accompanied by brighter episodes when dense clumps coalesce. We note that in rare massive galaxies at \( z \sim 6 \), the same process may feed \( \sim 10^9 M_\odot \) BH at the Eddington rate. High central gas column densities can severely obscure active galactic nuclei in high-redshift disks, possibly hindering their detection in deep X-ray surveys.

Key words: galaxies: active – galaxies: formation – galaxies: high-redshift – galaxies: nuclei – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The growth of massive black holes (BHs) and their associated active galactic nuclei (AGNs) are commonly assumed to be driven by gas inflows from galaxy mergers (Di Matteo et al. 2005; Hopkins et al. 2006). However, baryons are fed into high-redshift galaxies through cold streams, in which the contribution of smooth gas and small clumps is larger than that of mergers of mass ratio greater than 1:10 (Dekel et al. 2009; Brooks et al. 2009).

Cold accretion and high gas fractions in high-redshift disks trigger a violent instability, often characterized by giant star-forming clumps. Using analytic estimates (Section 2) and simulations (Section 3), we address the possibility that the gas supply for BH growth is provided by instability-driven inflows and evaluate the obscuration of AGNs in this model (Section 4).

2. INFLOW IN HIGH-REDSHIFT UNSTABLE DISKS

Many \( z \gtrsim 1 \) galaxies of stellar masses \( \sim 10^{10}–10^{11} M_\odot \) are rotating disks with giant clumps of \( \sim 10^9–10^9 M_\odot \) each (Elmegreen et al. 2007; Genzel et al. 2011). In most cases, ongoing mergers are not favored by gas kinematics (Genzel et al. 2008) and photometric properties (Elmegreen et al. 2009). Instead, high gas fractions of \( \sim 50\% \) (Daddi et al. 2010; Tacconi et al. 2010) and high gas velocity dispersions (Förster Schreiber et al. 2009) are consistent with gravitational instability and self-regulation at \( Q \sim 1 \).

The occurrence and persistence of gravitational disk instability at high redshift is a natural result of the high surface density of the cold disk component, which is maintained by the continuous gas supply through cold cosmic streams (Dekel et al. 2009a). The instability is predicted to be self-regulated in steady state for a few Gyr (Dekel et al. 2009b, DSC09), and cosmological simulations reveal clumpy disks that resemble the observed ones (Agertz et al. 2009; Ceverino et al. 2010). If giant clumps survive stellar feedback for a few \( 10^8 \) yr, they migrate into a central bulge (Noguchi 1999; Bournaud et al. 2007), as supported by observations (Genzel et al. 2008). Typical clumps seem to survive (Krumholz & Dekel 2010; Genzel et al. 2011), while the most luminous clumps could undergo faster disruption (Murray et al. 2010; Genzel et al. 2011). Nevertheless, the inflow is a robust feature of the disk instability, driven by gravity torques independently of the survivability of bound clumps (Gammie 2001; DSC09).

A key element in the self-regulated instability at \( Q \sim 1 \), given the high surface density, is maintaining strong turbulence, with a velocity dispersion of \( \sim 50 \text{ km s}^{-1} \) for circular velocity \( \sim 200 \text{ km s}^{-1} \), as observed in high-\( z \) disks. Supersonic turbulence dissipates in a few disk vertical crossing times (Mac Low 1999) and should therefore be continuously powered. An obvious source is the gravitational energy released when mass flows toward the center (DSC09; Elmegreen & Burkert 2010). Assuming that the incoming streams deposit mass and energy at the outskirts of the disk where they do not contribute directly to driving disk turbulence, as is suggested by cosmological simulations (Agertz et al. 2009; Ceverino et al. 2010), the main energy source is the inflow within the disk (Krumholz & Burkert 2010). This energy is transferred to velocity dispersion by gravitational torques involving massive clumps, transient features,
and smoother regions of the disk. Stellar feedback is unlikely to be the main driver of the turbulence, e.g., because the velocity dispersion is not observed to be tightly correlated with proximity to star-forming clumps (Förster Schreiber et al. 2009; Genzel et al. 2011).

The baryonic inflow rate $\dot{M}_b$ is estimated to be

$$\dot{M}_b \sim 0.2 \frac{M_d}{t_d} \left( \frac{\sigma}{V} \right)^2,$$

(1)

where $M_d$ is the disk mass, $t_d$ is the crossing time, $V$ is the circular velocity, and $\sigma$ is the one-dimensional velocity dispersion. At this rate, the power released by the inflow down the potential gradient, $M_d V^2$, compensates for the dissipative loss rate, $M_d \sigma^2 / t_{diss}$, where $M_d \sim 0.5 M_b$ is the disk gas mass and $t_{diss} \sim 3 t_d$ (M. Cacciato et al. 2011, in preparation). Similar estimates are obtained from the rate of energy exchange by clump encounters (DSC09, Equations (21) and (7)), and from the angular momentum exchange among the transient perturbations in a viscous disk (Gammie 2001; Genzel et al. 2008, DSC09, Equation (24)). Adopting $\sigma / V \sim 0.2$ and $t_d \sim 30$ Myr at $z = 2$, the inflow rate is

$$\dot{M}_b \simeq 25 M_{b,11}^{1/2} (1+z)^{3/2},$$

(2)

where $M_{b,11}$ is the disk mass in $10^{11} M_\odot$ and $(1+z)_3 = (1+z)/3$. Note that the $(1+z)^{3/2}$ scaling corresponds to the disk crossing time, proportional to the halo crossing time at fixed overdensity in a matter-dominated universe.

A continuity equation for the disk gas, being drained into star formation, outflows, and bulge, and replenished by streams, yields at $z \lesssim 3$ a steady state with $\dot{M}_b$ about one-third of the cosmological baryonic accretion rate (Bouché et al. 2010; Krumholz & Dekel 2011). With the latter being $\sim 80 M_{12} (1+z)^{1/2} M_\odot$ yr$^{-1}$ (Neistein et al. 2006, M12 being the halo mass in $10^{12} M_\odot$), this estimate is consistent with Equation (2) at $z = 3$, with a different redshift dependence for the cosmological inflow rate.

3. SIMULATIONS

We perform six idealized simulations using the Adaptive Mesh Refinement (AMR) code RAMSES (Teyssier 2002), with a density-dependent grid refinement strategy and a barotropic cooling model producing realistic phase-space interstellar medium (ISM) structure (Bournaud et al. 2010). The initial parameters of the six simulations are listed in Table 1. The smallest cell size is $\epsilon_{\text{AMR}} = 1.7$ or 3.4 pc in high-resolution (HR) runs and 10.2 pc in medium-resolution (MR) runs. Cells are refined if they contain a gas mass larger than $2 \times 10^3 M_\odot$, or more than 20 particles, or if the Jeans length is resolved by less than four

Table 1

| Simulation | $\epsilon_{\text{AMR}}$ (kpc) | $M_d(x10^{10} M_\odot)$ | $R_d$ (kpc) | $\dot{M}_b$ (SN) | $M_d(150 \text{ pc})$ | $M_d(1 \text{ kpc})$ | $\dot{M}_b$ (100 Myr$^{-1}$) |
|------------|-------------------------------|--------------------------|-------------|-----------------|----------------------|----------------------|-----------------------------|
| HR1        | 1.7                           | 7.0                      | 16          | 14%             | 0.5                  | 5.6                  | 7.2                         |
| MR1        | 10.2                          | 7.0                      | 16          | 14%             | 0.5                  | 5.2                  | 6.8                         |
| HR2        | 3.4                           | 1.5                      | 7           | 8%              | 0.5                  | 2.9                  | 3.2                         |
| MR2        | 10.2                          | 1.5                      | 7           | 8%              | 0.5                  | 1.3                  | 3.1                         |
| MR3        | 10.2                          | 3.3                      | 12          | 0%              | 0.5                  | 3.4                  | 6.5                         |
| MR4        | 10.2                          | 7.0                      | 16          | 14%             | 0.5–5               | 4.4                  | 6.9                         |

6 We used $0.5/3 \approx 0.2$ in Equation (1).
Figure 1. Surface density of gas and stars at two snapshots of simulation HR1. The gas is shown face-on (top) and edge-on (middle), the stars are shown face-on (bottom). To mimic optical images, the luminosity of each stellar particle is constant during its first 10 Myr then decreases as $t^{-0.7}$. Clumps A1 and A2 merge together between the snapshots.

(A color version of this figure is available in the online journal.)

Figure 2. Relative change in angular momentum per rotation period at radius $r$ in the disk of run HR1, as evaluated from the gravitational torques.

Figure 3 shows the net gas inflow rate across spherical shells about the stellar center of mass. Local inflow rates exceeding $10 \ M_\odot \ yr^{-1}$ are seen beyond the inner 1.5 kpc, dominated by clump migration. The inner kiloparsec is dominated by smooth inflow at a rate of $\sim 5 \ M_\odot \ yr^{-1}$. The mild decline between 1 kpc and 50 pc can be partly explained by a geometry effect, as the sphere radius becomes smaller than the disk thickness. This is demonstrated by the inflow rate through cylindrical boundaries being rather constant with radius (Figure 3, bottom panel). A large fraction of the inflow takes place above and below the mid-plane in the thick gaseous disk. An inflow rate of $1-2 \ M_\odot \ yr^{-1}$ nevertheless persists through the central few parsecs across spherical boundaries. We note that non-negligible outflows, presumably from stellar feedback, further reduce the net inflow rate in the central tens of parsecs. A comparison of runs HR1 and MR1 indicates no resolution effects on scales of 10–100 pc.

This gas inflow fuels star formation in the bulge. Galaxy HR1 at $t = 300$ Myr has a total SFR of $132 \ M_\odot \ yr^{-1}$, of which $16 \ M_\odot \ yr^{-1}$ is in the central kpc. This is less than the SFR of 42 and $31 \ M_\odot \ yr^{-1}$ in clumps A and B, but comparable to the $14 \ M_\odot \ yr^{-1}$ in clump C. At $t = 450$ Myr; the stellar bulge mass has grown from $9.8 \times 10^9 \ M_\odot$ to $2.2 \times 10^{10} \ M_\odot$. The persistence of star formation in the bulge as a result of disk instability is consistent with observations showing that bulges in clumpy disks are bluer than bulges in smooth disks (Elmegreen et al. 2009).
4. AGN OBSCURATION IN GAS-RICH DISKS

The central BH resides in a dense and thick gaseous disk (Figure 1), which could obscure an AGN. To quantify this, we computed the column densities over 60 random lines of sight through the centers of galaxy HR1 at $t = 330$ Myr and HR2 at $t = 380$ Myr. The results are insensitive to the choice of center, selected to be either the center of mass of old stars or the point of maximum vorticity. The foreground hydrogen column density $N_H$ was estimated over a cross-section corresponding to the minimum Jeans length, $4 \times 10^5 M_{\odot}$.

Figure 4 shows the distribution of $N_H$ for runs HR1 and HR2 and for various sets of inclinations. Fifteen percent of the lines of sight reach Compton thickness, $\log(N_H) \geq 24.1$, and 50% have $\log(N_H) \geq 23$, i.e., strong obscuration. The obscuration tends to be higher in the more massive disk HR1 where Compton thickness can be reached even for face-on orientations owing to the $\sim 1$ kpc thickness of the gas disk. The lower-mass galaxy HR2, perhaps more representative at $z < 2$, can reach Compton thickness almost exclusively for edge-on orientations.

If most gas in the central parsec lies in a torus, unresolved in our models, the obscuration on edge-on projections may be further enhanced and the dependence of obscuration on inclination may be stronger. Significant obscuration would still be present along most lines of sight, because the column densities measured in the simulations are on average not dominated by the central 10 pc.

5. DISCUSSION: ACCRETION ONTO THE BLACK HOLE

The isolated simulations presented here, using high gas fraction representative of $z \sim 2$ disks, have a disk inflow rate consistent with cosmological simulations of high-redshift stream-fed galaxies (Ceverino et al. 2010). They reach resolutions better than 2 pc, hence resolving the nuclear inflow down to scales at which other processes drive the actual small-scale BH accretion (Combes 2001). Only a fraction of the inflowing gas needs to make it all the way into the BH. The issues are similar to the case of merger-driven fueling, namely, getting rid of angular momentum while avoiding excessive star formation and AGN feedback. This is beyond the scope of our paper, and we limit ourselves to heuristic estimates.
One can assume that the local relation between the BH mass $M_{\text{BH}}$ and the bulge properties (mass $M_{\text{bul}}$ and velocity dispersion $\sigma$) is crudely valid at high redshift. If we adopt $M_{\text{BH}}/M_{\text{bul}} \sim 10^{-3}$ at $z = 0$, assume it scales as $\sigma^2$, and allow a cosmological scaling $\sigma^2 \propto (1 + z)$, then we obtain $M_{\text{BH}}/M_{\text{bul}} \sim 3 \times 10^{-3} \times z \sim 2$. A $z \approx 2$ galaxy of baryonic mass $10^{11} M_\odot$ hosts a BH of $\sim 10^8 M_\odot$, while in a gravitationally unstable steady state it is typically half-bulge and half-disk (DSC09). According to Equation (2), the average inflow rate through the disk into the bulge is $M_{\text{bul}} \sim 12.5 M_\odot \text{yr}^{-1}$. If the ratio of average accretion rates into bulge and BH follow the ratio of the corresponding masses, the BH accretes on average at $M_{\text{BH}} \sim 0.04 M_\odot \text{yr}^{-1}$, which is 1\%–2\% of the Eddington rate (assuming a 0.1 efficiency for mass-to-energy conversion). The corresponding bolometric luminosity is $2 \times 10^{44} \text{erg s}^{-1}$. With typically 1\%–5\% in X-rays, we estimate on average $L_X \sim 10^{42} - 10^{43} \text{erg s}^{-1}$, scaling with galaxy mass and with $(1 + z)^{3.5}$. While the average luminosity would be modest, short episodes of higher accretion rate, possibly up to the Eddington level, occur during the central coalescence of migrating giant clumps—which could also bring with them seed BHs (Elmegreen et al. 2008a).

At very high redshift, the same process could feed brighter AGNs in rare massive systems (Di Matteo et al. 2011), provided that unstable disks indeed form there. The average inflow rate increases with redshift (Equation (2)), such that a $z = 6$–10 disk can support continuous accretion at the Eddington rate. If a regulated quasar mode if $M_{\text{disk}}$ can support continuous accretion at the Eddington rate increases with redshift (Equation (2)), such that a $z = 6$–10 disk can support continuous accretion at the Eddington rate.

The violent instability phase should end when the cosmological accretion rate declines and the system becomes stellar dominated. We expect less massive galaxies to remain unstable for longer times, because they retain higher gas fractions—perhaps the aspect of the downsizing of star formation (e.g., Juneau et al. 2005). This can result from the regulation of gas consumption in smaller galaxies (Dekel & Silk 1986; Krumholz & Dekel 2011) and from the continuation of cold accretion to lower redshift for lower-mass halos (Dekel & Birnboim 2006). It induces an inverse gradient of gas fraction with galaxy mass (as observed, Kannappan 2004) and a downsizing in gravitational instability which could result in downsizing of BH growth. This is a longer growth phase into later redshifts in lower-mass galaxies, with $\sim 10^{11} M_\odot$ galaxies growing BHs mostly at $z > 1$ in their unstable disk phase, while clumpy disks of $\sim 10^{10} M_\odot$ may show AGN activity even after $z \sim 1$.

Simulations were performed at CCRT and TGCC under GENCI allocation 2011-GEN2192. We acknowledge discussions with Françoise Combes, Bruce Elmegreen, Tiziana Di Matteo, James Mullaney, a constructive referee report, and support from grants ERC-StG-257720 (F.B., S.J.), CosmoComp ITN (F.B., R.T., S.J.), ISF 6/08, GIF-G-1052-104.7/2009, NSF AST-1010033, and a DIP grant (A.D.).

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