On rapid migration and accretion within disks around supermassive black holes

B. McKernan\textsuperscript{1,2,3}, K.E.S. Ford\textsuperscript{1,2,3}, W. Lyra \textsuperscript{2}, H.B. Perets\textsuperscript{4}, L.M. Winter\textsuperscript{5,7} & T. Yaqoob\textsuperscript{6}

\textsuperscript{1}Department of Science, Borough of Manhattan Community College, City University of New York, New York, NY 10007
\textsuperscript{2}Department of Astrophysics, American Museum of Natural History, New York, NY 10024
\textsuperscript{3}Graduate Center, City University of New York, 365 5th Avenue, New York, NY 10016
\textsuperscript{4}Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138
\textsuperscript{5}Center for Astrophysics \& Space Astronomy, University of Colorado, Boulder, CO 80303
\textsuperscript{6}Department of Physics \& Astronomy, Johns Hopkins University, Baltimore, MD 21218
\textsuperscript{7}Hubble Fellow

ABSTRACT
Galactic nuclei should contain a cluster of stars and compact objects in the vicinity of the central supermassive black hole due to stellar evolution, minor mergers and gravitational dynamical friction. By analogy with protoplanetary migration, nuclear cluster objects (NCOs) can migrate in the accretion disks that power active galactic nuclei by exchanging angular momentum with disk gas. Here we show that an \textit{individual} NCO undergoing runaway outward migration comparable to Type III protoplanetary migration can generate an accretion rate corresponding to Seyfert AGN or quasar luminosities. Multiple migrating NCOs in an AGN disk can dominate traditional viscous disk accretion and at large disk radii, ensemble NCO migration and accretion could provide sufficient heating to prevent the gravitational instability from consuming disk gas in star formation. The magnitude and energy of the X-ray soft excess observed at $\sim 0.1 – 1$ keV in Seyfert AGN could be explained by a small population of $\sim 10^2 – 10^3$ accreting stellar mass black holes or a few ULXs. NCO migration and accretion in AGN disks are therefore extremely important mechanisms to add to realistic models of AGN disks.

Key words: galaxies: active – galaxies: individual – galaxies: LINERs – techniques: spectroscopic – X-rays: line – emission: accretion – disks: galaxies

1 INTRODUCTION
Gigantic gas disks feeding supermassive black holes are prone to the gravitational instability beyond $\sim 10^3$ Schwarzschild radii (e.g. Shlosman & Begelman 1987; Goodman \& Tan 2004). In order to maintain large-scale gas disks implied by huge accretion rates for AGN lifetimes, additional heating of the outer disk is required (Sirko \& Goodman 2003), but a universal heating mechanism has yet to be found (e.g. Collin \& Zahn 2008). The converse of this problem is that in low luminosity AGN, the implied low accretion rates (Kauffmann \& Heckman 2009) should make it impossible to maintain an inflated, obscuring torus in these objects (He 2008) via radiation pressure from the central engine alone (Pier \& Krolik 1992).

Here we discuss the interaction of the cluster of stars and compact objects in galactic nuclei with AGN accretion disks. Nuclear cluster objects (NCOs) with orbits coincident with the disk can accrete strongly and exchange angular momentum with disk gas and each other. By migrating and accreting within the disk, NCOs can play a role in the problem of disk heating and the inferred AGN accretion rate. The interaction of NCOs with AGN disks has long been discussed (e.g. Ostriker 1983; Syer, Clarke \& Rees 1991), while NCO migration within AGN disks (e.g. Artymowicz et al. 1993; Goodman \& Tan 2004; Levin 2007) and NCO accretion (e.g. Nayakshin \& Sunyaev 2007; McKernan et al. 2010, 2011) must play a role in models of the AGN central engine. In this Letter, we emphasize the importance of runaway NCO migration within AGN disks due to the torque produced by gaseous fluid elements in the disk as they perform horseshoe U-turns near the NCO. We point out that an \textit{individual} NCO migrating rapidly due to co-orbital corotation torque (Masset \& Papaloizou 2002) can drive accretion rates that dominate the viscous disk accretion rates believed to power AGN. We also point out that NCO accretion can account for
the soft X-ray excess observed in Seyfert AGN and the inflation of the accretion flow at large radii even when radiation pressure from the central engine is very low. We conclude that realistic models of AGN central engines must include a population of migrating and accreting NCOs.

2 NCOS AND THE ANALOGY WITH PROTOPLANETARY DISKS

The largest, supermassive, black holes in the Universe ($M_{BH} \sim 10^6 - 10^9 M_{\odot}$) live in galactic centers (e.g. Kormendy & Richstone 1995). These behemoths are expected to be closely surrounded by a dense nuclear cluster of objects as a result of stellar evolution, dynamical friction, secular evolution and minor mergers (e.g. Morris 1993; Miralda-Escudé & Gould 2000; Merritt 2010). In our own Galactic nucleus, the implied distributed mass within ~1pc is ~10% - 30% of the mass of SgrA* itself (Schoedel et al. 2002). Mass segregation may play a role in determining the NCO population (e.g. Alexander 2005; Merritt 2010), but we should expect ~10^6 NCOs of average mass ~1M_{\odot} within 1pc of a SgrA* black hole. In a given nucleus, the exact proportion of stellar and compact NCOs will depend on the history of the nucleus host galaxy (e.g. McKernan et al. 2010). If a large quantity of gas arrives in the innermost pc of a galactic nucleus, it will likely lose angular momentum and accrete onto the central supermassive black hole, but in doing so must also interact with the NCO population. Depending on the aspect ratio of the disk that forms, a few percent of NCOs orbits are likely to coincide with the accretion flow. A small percentage of NCOs coincident with the disk could lead to few\times10^3 NCOs in the accretion flow around a SgrA* black hole. While multi-object migration in disks is an open problem beyond the scope of this Letter, the existence of one migrator can have important consequences for the observational appearance of galactic nuclei. Given the number of NCOs available, it is probable that the effects described below are important in many AGN disks.

By analogy with protoplanetary disk theory, and following e.g. (Goodman & Tan 2004; Levin 2007), we assume that NCOs in thin AGN disks exchange angular momentum with disk gas and migrate. This assumption is not unreasonable since the mass ratios involved, disk densities and related physics (gravitational instability and magneto-rotational instability (MRI)) are similar for AGN and protoplanetary disks at large radii, although temperatures differ substantially at small radii. AGN disks at small radii are relativistic (both Special and General). However, fully general relativistic global MHD disks appear globally similar to their Newtonian counterparts until close to the radius of last stable orbit ($R_{isc}$) (e.g. Noble, Krolik & Hawley 2000). Likewise, self-gravity in AGN accretion disks will be important (e.g. Shlosman & Begelman 1987; Artymowicz et al. 1993). However, disk self-gravity does not appear to have a major effect on the torques involved in satellite migration, except possibly accelerating migration outwards (Baruteau & Masset 2008). Obviously, simulations are required to understand the parallel with AGN disks in detail and we will return to this in future work.

The aspect of protoplanetary disk theory that most concerns us here is that dense satellites perturb disk symmetry, suffer a net torque and exchange angular momentum with disk gas (see e.g. Armitage 2010; Lyra et al. 2010; Paardekooper et al. 2010 and references therein). Even where the disk is self-gravitating(e.g. Baruteau & Masset 2008), or ionized enough to maintain MRI (e.g. Nelson & Papaloizou 2004), the torque can operate very effectively in exchanging angular momentum between the satellite and the gas. As a result, the satellite can migrate within the gas disk, sometimes very rapidly indeed. In classical protoplanetary disk theory, Type I migration (small migrator, $q \leq 10^{-5}$) occurs on a timescale of $\tau I = \frac{1}{N} \frac{M}{q \Sigma} \left(\frac{h}{\alpha}\right)^2 \frac{1}{\omega}$ (1)

where $M$ is the central mass, $q$ is the ratio of the satellite mass to the central mass, $\Sigma$ is the disk surface density, $h/r$ is the disk aspect ratio and $\omega$ is the satellite angular frequency. The numerical factor $N$ depends on the ratio of radiative to dynamical timescales and is a function of the power-law indices of $\Sigma$, $T$ and entropy (Lyra et al. 2010; Paardekooper et al. 2010). Larger (Type II) migrators ($q > h$) can open gaps in the disk and migrate inwards on the viscous accretion timescale of the disk, $\tau s$, (i.e. $\tau I \gg \tau s$). An intermediate form of migration (Type III) can occur where the migrator ($q \sim 10^{-5} - 10^{-4}$) perturbs the disk, but not enough to open a gap (e.g. Masset & Papaloizou 2003; Pepliński et al. 2008a). This form of migration can occur very quickly in either direction and may in fact runaway onwards depending on the flow of gas around the migrator (Pepliński et al. 2008b). Type III migration occurs on approximately the dynamical (orbital) timescale of the disk ($\tau III \sim \tau o$).

3 AGN ACCRETION AND NCOS

Accretion onto the central black hole in AGN occurs via the transfer of angular momentum between parcels of gas in a disk. A mass of gas moving inwards ($m_{in}$) in the disk will drive a mass of gas outwards ($m_{out}$), conserving angular momentum so that $m_{in}/m_{out} \sim \sqrt{R_{out}/R_{in}}$ for a Keplerian disk. In the case of the classic stationary thin disk, the mass flux through the disk around a Schwarzschild black hole (and inferred accretion rate) is given by (Shakura & Sunyaev 1973)

$$\dot{M} = \frac{2 \pi \alpha \Sigma c^2}{\omega \left(1 - (R_{isc}/R_{in})^{1/2}\right)} = \frac{\Delta M}{\Delta t} \tag{2}$$

where $\alpha$ is the viscosity parameter, $c$ is the sound speed and $\Delta t$ is the viscous timescale of the disk, given by $\tau s \sim \alpha^{-1} (h/r)^{-2} \tau o$. Friction in the viscous disk generates luminosity which is parameterized as $\eta M^2 c^2$ where $\eta$ is the efficiency of gravitational energy release ($\eta \sim 0.06$ for a Schwarzschild metric (Shakura & Sunyaev 1973) up to ~0.42 for a maximally spinning Kerr black hole) for a standard thin disk. Heat release per unit disk area for a thin disk in a Keplerian potential is $\propto M / r^3$ (e.g. Krolik 1994). Now, if we substitute the outflowing gas parcel ($m_{out}$) above with an out-migrating NCO of identical mass, $m_{in}$ will be identical, but the inflow timescale will now be the...
NCO migration timescale ($\tau_m$) rather than the viscous disk timescale ($\tau_\nu$). The disk luminosity and heating generated by the inflow is still produced by the same underlying microphysics (i.e. gas friction in the disk). The only difference is that $\Delta t$ in equation 2 is now the migration timescale. If $\tau_m \ll \tau_\nu$ then $M$ due to migration can dominate viscous accretion.

Figure 1 shows the relevant timescales as a function of radius, using a thin accretion disk surrounding a $10^8 M_\odot$ supermassive black hole with $M$ constant (at 0.5 Eddington) as a function of radius (Sirko & Goodman 2003). $\tau_{dyn}$ is the dynamical (or orbital) timescale and the relevant timescale for Type III migration and $\tau_Q \sim \alpha^{-1} \tau_{dyn}$ is the local disk heating timescale. $\tau_\nu$ has been calculated from eqn. 1 for a $q = 10^{-6} (10^2 M_\odot)$ NCO migrator in the adiabatic limit using $\Sigma^{-2}, T \propto r^{-3/4}$ from Sirko & Goodman (2003). $\tau_\nu$ truncates at $\sim 500 r_g$ from eqn. 1 below and the kink in $\tau_\nu$ comes from model parameters of the disk in Sirko & Goodman (2003).

3.1 NCO migration in AGN disks

For an NCO to actually migrate within the gas disk, the gas in a ring co-rotating with the NCO should have an angular momentum comparable to that of the NCO. This condition corresponds to

$$2\pi r \Delta r \sim m$$

where $\Sigma$ is the disk surface density, $r$ is the distance of the NCO from the supermassive black hole, $\Delta r$ is the width of the co-rotating gas region (roughly the Hill sphere radius) and $m$ is the mass of the NCO. The radius of the Hill sphere for a compact object on a circularized orbit ($e = 0$) is $r_H \approx rq^{1/3}$ where $r$ is the orbital radius and $q$ is the mass ratio of the compact object to the central black hole. Assuming $\Delta r \sim rq^{1/3}$, the innermost disk radius (in units of gravitational radii) at which migration can occur is

$$R_{in}(r_g) \sim \frac{10^3 m_{in}^{1/2}}{q^{1/6} M_8 \Sigma^{1/2} r_g}$$

where $m_{in}$ is the mass of the migrator in units of $M_\odot$, $M_8$ is the mass of the supermassive black hole in units of $10^8 M_\odot$, $q = m_{in}/M_8$ and $\Sigma$ is the surface density of the AGN disk in units of $g$ cm$^{-2}$.

Most NCOs will undergo Type I migration ($q < 10^{-3}$) in thin AGN disks. Exceptions include OB stars and stellar mass black holes around $10^6 M_\odot$ black holes, which at $q \sim 10^{-3} - 10^{-2}$ could undergo rapid Type III migration in the disk. Around $10^8 M_\odot$ black holes, only intermediate mass black holes $> 10^4 M_\odot$ could undergo rapid Type III migration. Type II migration by IMBHs or supermassive stars with $q > 10^{-4}$ could open gaps in thin AGN disks (e.g. Goodman & Tan 2004). Gaps in an accretion disk would truncate NCO migration, possibly leading to three-body interactions with IMBHs. Multiple IMBHs in an AGN disk would show up as deficits in broad spectral lines that vary collectively on a timescale of $\tau_\nu$.

Figure 2 shows $M$ as a function of radius for the accretion disk from Fig. 1. The model disk of Sirko & Goodman (2003) assumes constant $M$ with radius, so we show the 10% Eddington mass accretion rate for a $10^8 M_\odot$ as a dashed
line. The solid line represents a \( q = 10^{-5} \) NCO undergoing rapid Type III migration and doubling its radius in \( \sim 10^2 \) orbits, following the simulated \( \sim 50\% \) increase in radius in a few \( 10\) s of orbits for protoplanetary satellites (e.g. Masset & Papaloizou 2003). The dash-dot line represents a \( q = 10^{-6} \) NCO undergoing Type I migration and doubling its radius on the Type I migration timescale. We note several important points from Fig. 2. First, the runaway migration of a single \( q = 10^{-5} \) NCO near \( \sim 10^5 r_g \) can generate the Eddington mass accretion rate in an AGN, corresponding to quasar-like luminosity. Based on the environment of SgrA*, up to a few \( 10^5 \) NCOs could lie within \( 1\) pc of the \( 10^5 M_\odot \) in Fig. 2 leading to a large NCO population in the accretion disk. Second, since runaway migration is greatest for large disk surface density (Masset & Papaloizou 2003), runaway NCO migration is most likely to occur deeper in the AGN potential where it can generate very high \( \dot{M} \). Third, if the speed or magnitude of runaway migration is greater for NCOs in AGN disks than in (Masset & Papaloizou, 2003), \( \dot{M} \) in Fig. 2 could be substantially higher. The local disk heating (\( \propto \dot{M}/r^2 \)) associated with runaway migration within a few thousand \( r_g \) exceeds local viscous heating for Seyfert AGN (\( \sim 0.1\mathrm{L}_{\mathrm{Edd}} \)) by a factor of a few. If \( \dot{M} \) due to viscous accretion drops with radius, local heating due to migration at large radii (\( \propto \dot{M}/r^3 \)) could dominate viscous heating, particularly since the NCO population should increase as the radius squared. Note that, if the NCO migrates inwards rather than outwards, the Type III and Type I migration curves in Fig. 2 will be lower by a factor of \( \sqrt{2} \) since \( m_{\mathrm{out}}/m_{\mathrm{out}} = \sqrt{R_{\mathrm{out}}/R_{\mathrm{in}}} \) for a Keplerian disk. Interestingly, an NCO that is not tidally disrupted while accreted onto the black hole should correspond to a low luminosity (\( \eta M c^2 \)) mode of accretion.

### 3.2 Clearing out & tidal disruption

The very large initial number of NCOs expected in the AGN disk should lead to a rapid clearing out of NCOs due to three-body interactions. Naively we might expect roughly half the cleared out NCOs to be ejected from the disk and half to be accreted onto the supermassive black hole. The clearout duration (\( \tau_{\mathrm{clear}} \)) could constitute a very high accretion rate (\( \sim 0.5\dot{M}_{\mathrm{NCO}}/\tau_{\mathrm{clear}} \)) onto the supermassive black hole. If the clearout occurs e.g. on the average dynamical timescale at \( 10^6 r_g \) (\( \sim 0.1\mathrm{Myr} \)) in Fig. 1 for \( \sim 10^6 \) NCOs in the disk surrounding a \( 10^5 M_\odot \) black hole, the NCO accretion rate is \( \dot{M}_{\mathrm{Edd}} \) for \( \sim 0.1\mathrm{Myr} \). Compact NCOs are less effected by tidal shearing and so may represent the most radiatively inefficient mode of accretion while tidally disrupted stellar NCOs will contribute to the AGN luminosity (\( \eta M c^2 \)) during this phase. After clearing out, a small population of migrators should be left in the thin AGN disk. However, gradual orbital decay of NCOs intersecting the disk must occur over time (e.g. Ostriker 1983; Artymowicz et al. 1993, Miralda-Escudé & Gould 2003). Phenomena such as resonant relaxation (Rauh & Tremaine 1996), and the Kozai mechanism (e.g. Subr & Kasai 2005; Chand 2009) will contribute to NCO capture by the disk, although on timescales longer than the AGN disk lifetime (\( \sim 10\mathrm{Myrs} \)) in most cases. The capture rate for NCOs on small radius orbits is the dominant effect over the AGN lifetime (e.g. Artymowicz et al. 1993), so \( \sim 10^{3-4} \) NCOs could be added to the disk in Fig. 2 within \( \sim 10^5 r_g \) over a 10Myr disk lifetime.

### 4 ACCRETION ONTO NCOs

NCOs can have very different appearances depending on their accretion rates from the disk. The most massive stellar NCOs, accreting rapidly from the disk, can become luminous blue, Wolf-Rayet stars (e.g. Artymowicz et al. 1993). Minor black holes accreting rapidly can look like high mass X-ray binaries or ULXs depending on \( M_{\mathrm{BH}} \) (see e.g. McKernan et al. 2010, 2011). Neutron stars accreting at a high rate can spin up rapidly becoming pulsars, contributing to (quasi) periodic signals in the radio and X-ray bands. Accreting white dwarfs will heat up and contribute to the overall IR flux and generate Type Ia supernovae. If the mass of the accreting NCO approaches \( q \sim 10^{-5} \), the NCO may begin to migrate very rapidly in the disk (see above). For NCOs not in the disk, sporadic accretion will occur onto compact NCOs punching through the disk on orbits on small fractions of their orbital timescales, contributing to observed volume filling broad-line and narrow-line emission (e.g. Vilkoviskii & Czerny 2002, Navakshin & Sunyaev 2007) point out that a stellar mass black hole accreting from a dense gas disk can accrete at near Eddington rates (\( M_{\mathrm{Edd}} \)). By contrast, strong magnetic fields may inhibit accretion onto neutron stars and white dwarfs (Toronina et al. 2003). For a population of \( \sim 10^4 \) NCOs in the disk around a SgrA* black hole, with fiducial compact NCO population of (Alexander 2003): 1%(black holes, accreting at \( M_{\mathrm{Edd}} \)), and 3%(neutron stars) and 20%(white dwarfs) accreting at 0.1\( M_{\mathrm{Edd}} \), the total compact NCO luminosity contribution corresponds to \( \sim 10^{-3} M_{\mathrm{Edd}} \) of the central supermassive black hole. Therefore, accretion onto compact NCOs could dominate viscous disk accretion in lower luminosity AGN and LINERs (e.g. Kaufmann & Heckman 2009). A single \( 10 M_\odot \) black hole accreting at \( \sim M_{\mathrm{Edd}} \) located \( \sim 1\) pc from a \( 10^{42} \) erg/s AGN ionizing continuum will dominate the local ionization field within \( \sim 0.05 \) pc. A population of \( \sim 10^8 \) such NCO accretors distributed around \( \sim 1 \) pc would dominate low luminosity AGN heating of the outskirts of the disk.

A soft X-ray bump (the 'soft excess') of \( \sim 10^{40-41} \) erg s\(^{-1} \) and uncertain origin is observed in many Seyfert AGN, with constant temperature over four orders of magnitude in black hole mass (e.g. Crummy et al. 2006, Gierlinski & Done 2003, McKernan et al. 2002). The magnitude and constant temperature of the soft excess could be explained either by \( \sim 10^2 - 10^3 \) stellar mass black holes accreting like Galactic high-mass X-ray binaries (e.g. Remillard & McClintock 2006) or by a handful of ULXs (McKernan et al. 2011). If there is a correlation between the soft excess and powerlaw luminosities (Winter et al. 2009), there may be a link between NCO accretion rate and accretion onto the supermassive black hole. Intrinsic soft excess variability will depend on the number of NCO accretors. In the limit of a single highly luminous ULX with mass ratio \( q \), the soft excess will vary on timescales \( q t_p \), where \( t_p \) is the timescale of variation of the powerlaw component. In the limit of a large number of accreting NCOs, the magnitude of
the intrinsic soft excess luminosity variability will be much smaller than powerlaw variability.

The heat liberated by migration (\( \propto \dot{M}/r^3 \)) drops quickly with increasing radius. Unless the migration is rapid (large \( \dot{M} \)), heating due to NCO accretion should dominate at large radii, since the number of NCOs should grow as the square of the radius. A large enough number of accreting compact objects (black holes and neutron stars) can generate sufficient hard radiation/radiation pressure to inflate the accretion flow at large radii, regardless of the rate of accretion onto the supermassive black hole, so we should expect inflated accretion flows in even low luminosity galactic nuclei. The Type I migration timescale should increase as \((h/r)^2\), so migration should become inhibited at large radii, unless NCOs accrete enough so that \( q > 10^{-5} \) and rapid Type III migration can occur.

### 5 CONCLUSIONS AND FUTURE WORK

A cluster of stars and compact objects is expected in the central pc of most galactic nuclei. The exchange of angular momentum between an accretion disk of gas and nuclear cluster objects (NCOs) can lead to NCO migration and NCO accretion. Here we emphasize that runaway outward migration of NCOs in AGN disks, similar to Type III migration in protoplanetary disks, generates accretion rates that can dominate traditional viscous disk accretion rates. Disk heating due to NCO migration/accretion can inflate the accretion flow and counter the gravitational instability at large radii. Inflation of the accretion flow due to compact objects in the disk may account for obscuring structures in LINERs and low luminosity AGN. A small population of accreting stellar mass black holes can account for the magnitude and constant temperature of the soft X-ray excess observed in Seyfert AGN.

We also note some important implications for future work: 1) A large population of migrating NCOs in a gas disk could help close the final parsec gap in stalled supermassive black hole binary mergers (e.g. Lodato et al. 2000) by exchanging angular momentum with the SMBH. 2) NCO clear-out from AGN disks may yield a population of high velocity NS and WD in galactic bulges and haloes, together with high velocity stars (e.g. Perets et al. 2009). High velocity pulsars in our own Galaxy have velocities similar to escape speeds from around Sgr A* (e.g. Cordes & Chernoff 1998). 3) Differences between NCO populations in different nuclei could account for observed differences in AGN in spiral and elliptical hosts. 4) IMBHs build up mass most efficiently as NCOs in an AGN disk and ULX signatures should be observed in galactic nuclei (McKernan et al. 2011). 5) Radiatively inefficient, thick \((h/r > 0.1)\) disks may drive more out-migration than thin-disks. 6) NCO migration in a disk threaded with magnetic fields can drive MHD outflows.

We conclude that realistic models of AGN disks should include populations of migrating and accreting NCOs.

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